

# Search for Electroweak Top Quark Production at DØ



The Tevatron & DØ Experiment



Top Quarks & Single Top Production



Selection Cuts & Background Estimation



Matrix Element Technique



Preliminary Results

Thomas Gadfort

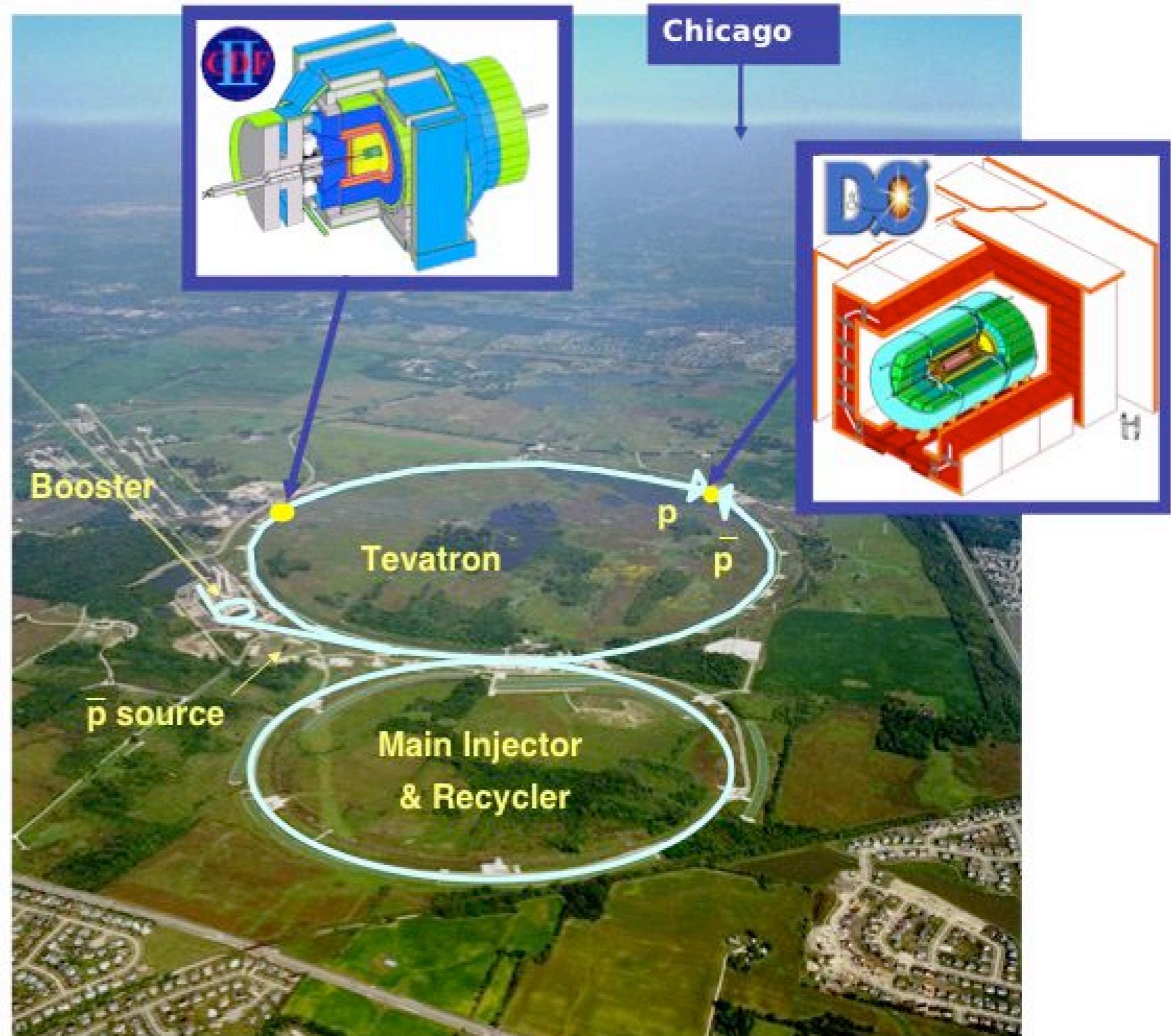
University of Washington

October 3, 2006

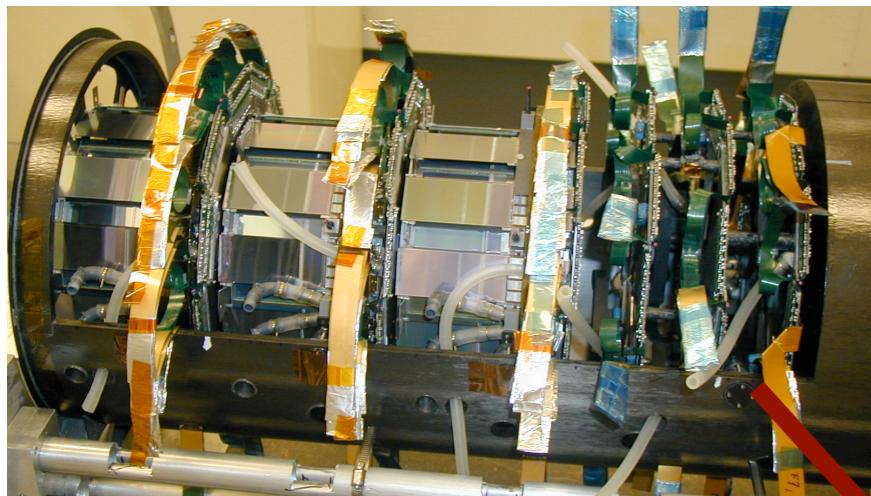
Fermilab Seminar

# The Tevatron at Fermilab

- ◆ Tevatron is a p-pbar collider with  $\hat{s} = 1.96 \text{ TeV}$
- ◆ RunI: 1992-1996
  - ❖ Top quark discovered
- ◆ RunII: 2001 - Present
  - ❖ >10x Run I dataset
  - ❖ Still no Higgs
  - ❖ Still no SUSY
- ◆ Currently, the only place to directly study the top quark



# Run II DØ Detector

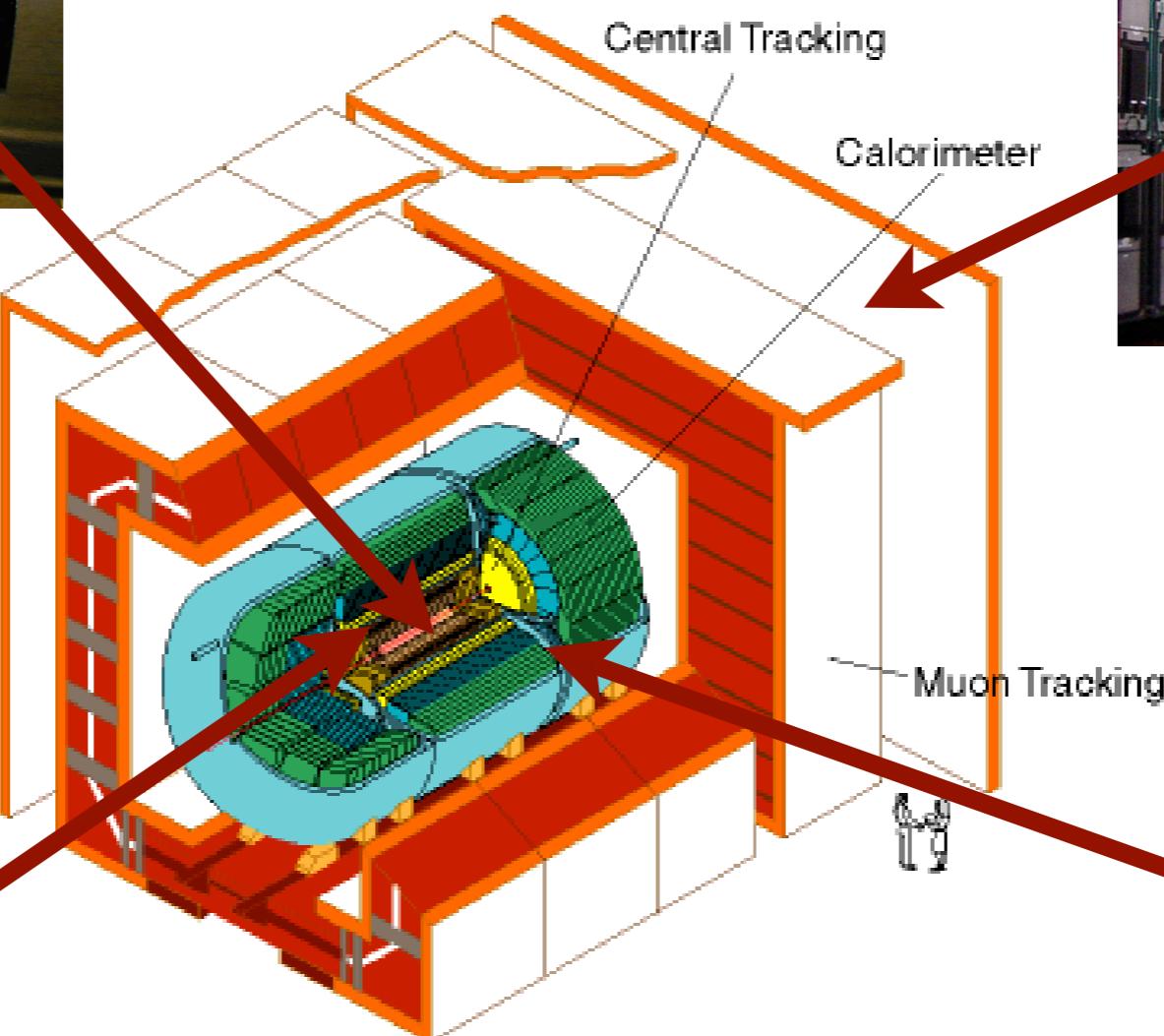
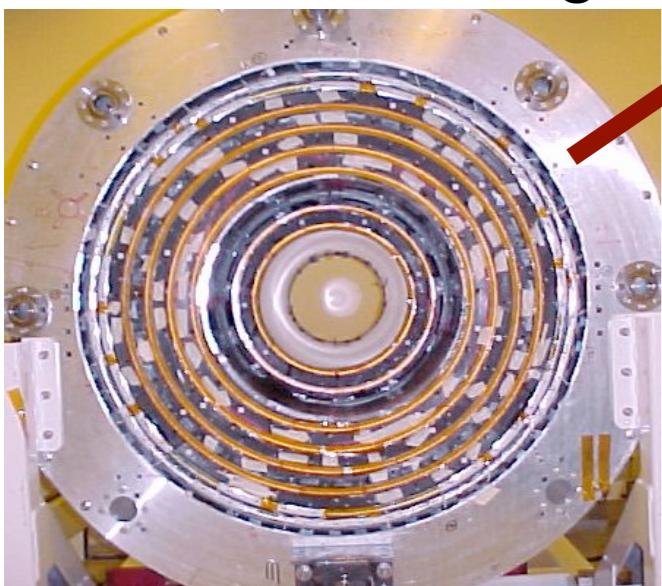


## Silicon Detector

Vertex measurement  
tracking close to PV

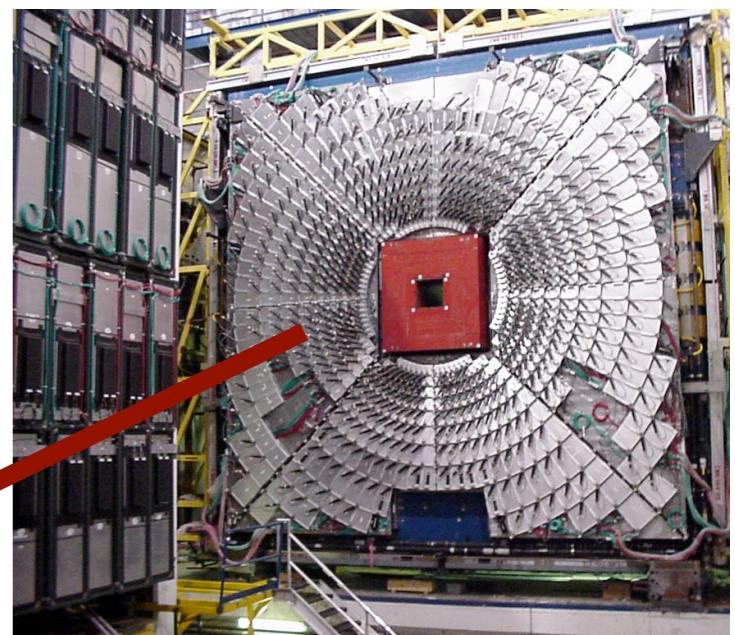
## Fiber Tracker

Charged particle tracking  
momentum + charge



## Muon System

Drift chambers / scintillators  
Muon position and tracking



## Liquid Ar/Ur Calorimeter

Energy measurement for  
electrons, photons, and  
hadrons

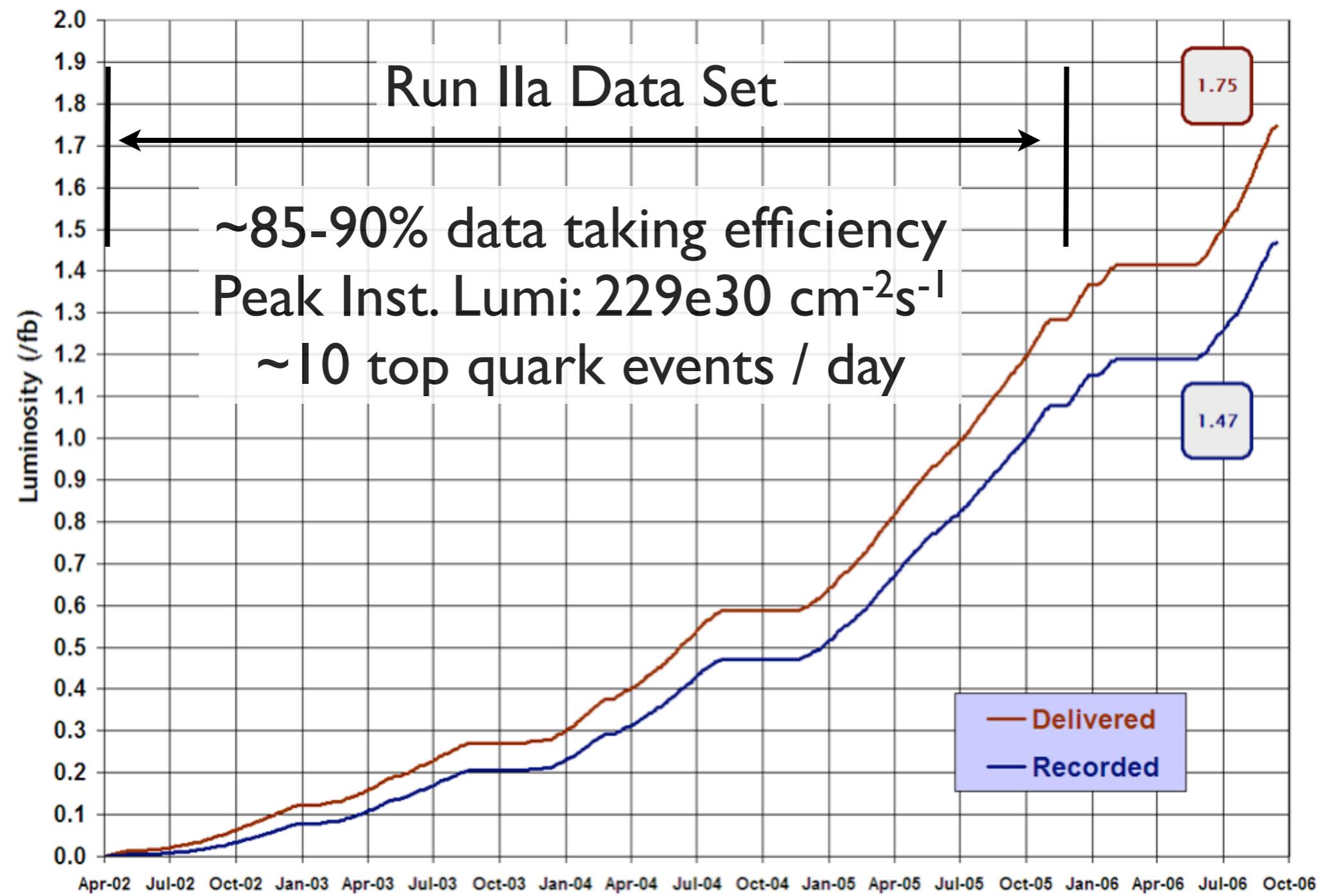


# Run II Data Taking



## Run II Integrated Luminosity

19 April 2002 - 1 October 2006



# The Top Quark: Properties & Production

◆ Top quark was discovered in 1995 at the Tevatron by DØ and CDF

◆ Heaviest of all the fermions

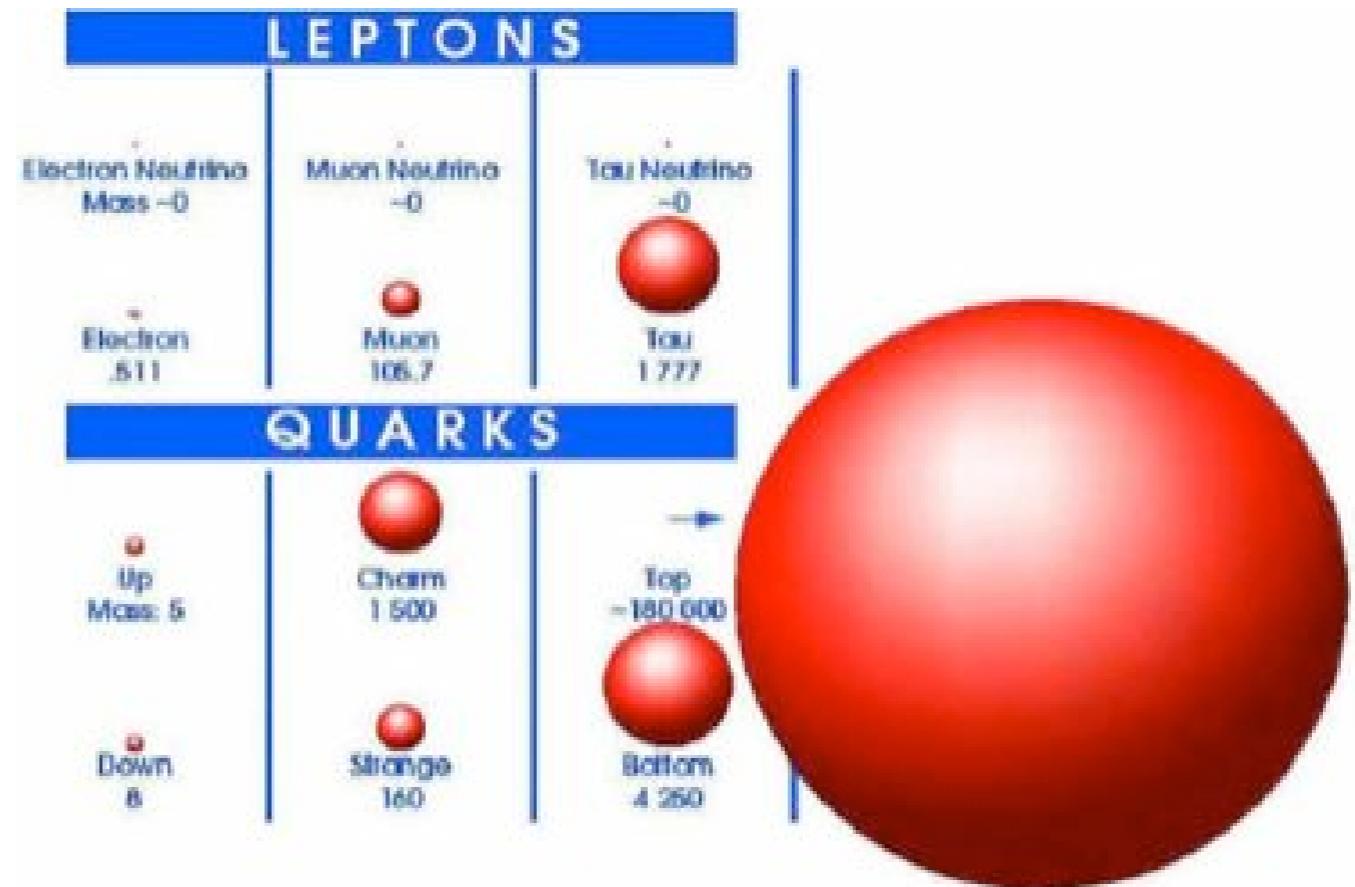
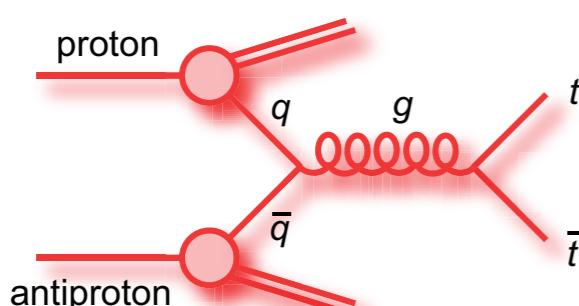
$$M_t = 171.4 \pm 2.1$$

$$y_t = \frac{\sqrt{2}M_t}{v} \sim 1$$

◆ Short lifetime

❖  $\Gamma_t = 1.5 \text{ GeV} \sim 10 \times \Lambda_{\text{QCD}}$

❖ Daughter particles  
retain spin information

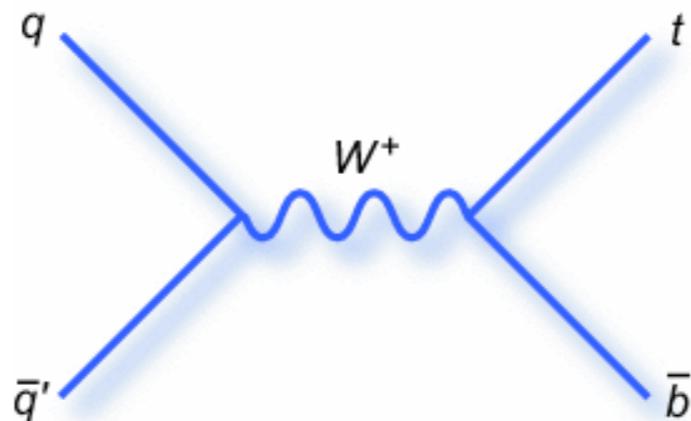


- ◆ Main production mode at the Tevatron is QCD pair production (85%  $qq$  vs 15%  $gg$ )
- ◆ NLO cross section is 6.67 pb @  $\hat{s} = 1.96 \text{ TeV}$

# Single Top Quark Production

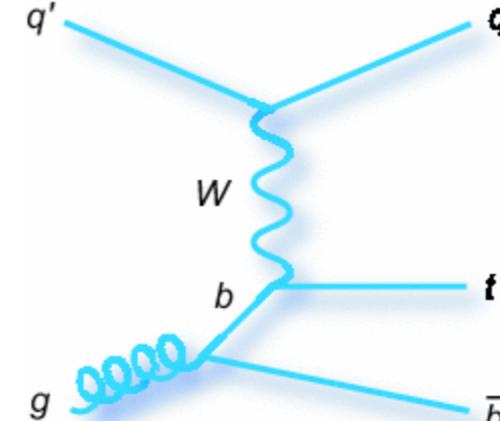
- ◆ Top quarks can also be produced via an electroweak interaction.
- ◆ The two main processes available at the Tevatron are defined by W boson virtuality

s-channel



$$\sigma_s = 0.88 \pm 0.07 \text{ pb}$$

t-channel



$$\sigma_t = 1.98 \pm 0.21 \text{ pb}$$

Harris, Laenen, Phaf, Sullivan, Weinzierl, PRD 66 (02) 054024  
Sullivan hep-ph/0408049

- ◆ Current Limits from the Tevatron:

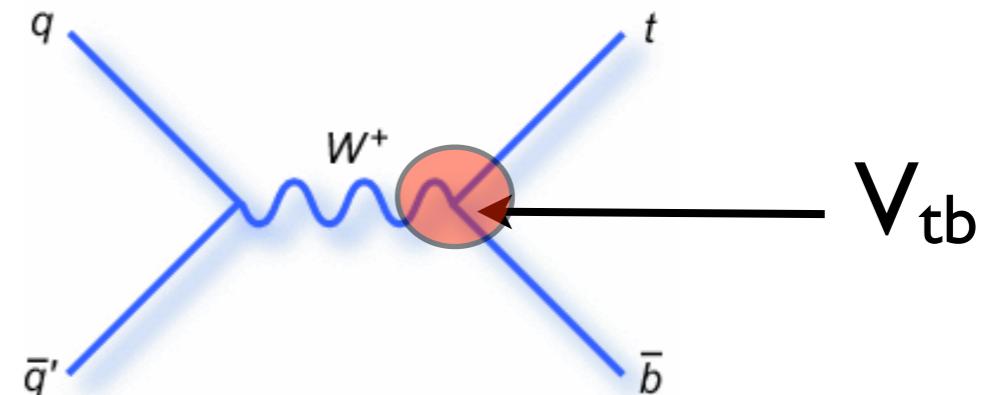
❖ DØ with  $370 \text{ pb}^{-1}$ :  $\sigma_s < 5.0 \text{ pb}$        $\sigma_t < 4.4 \text{ pb}$

❖ CDF with  $675 \text{ pb}^{-1}$ :  $\sigma_s < 3.2 \text{ pb}$        $\sigma_t < 3.1 \text{ pb}$        $\sigma_{s+t} < 3.4 \text{ pb}$

# Why Is Single Top Interesting?

## ◆ W-t-b vertex in production

- ❖ Direct access to  $|V_{tb}|$  through production cross section measurement

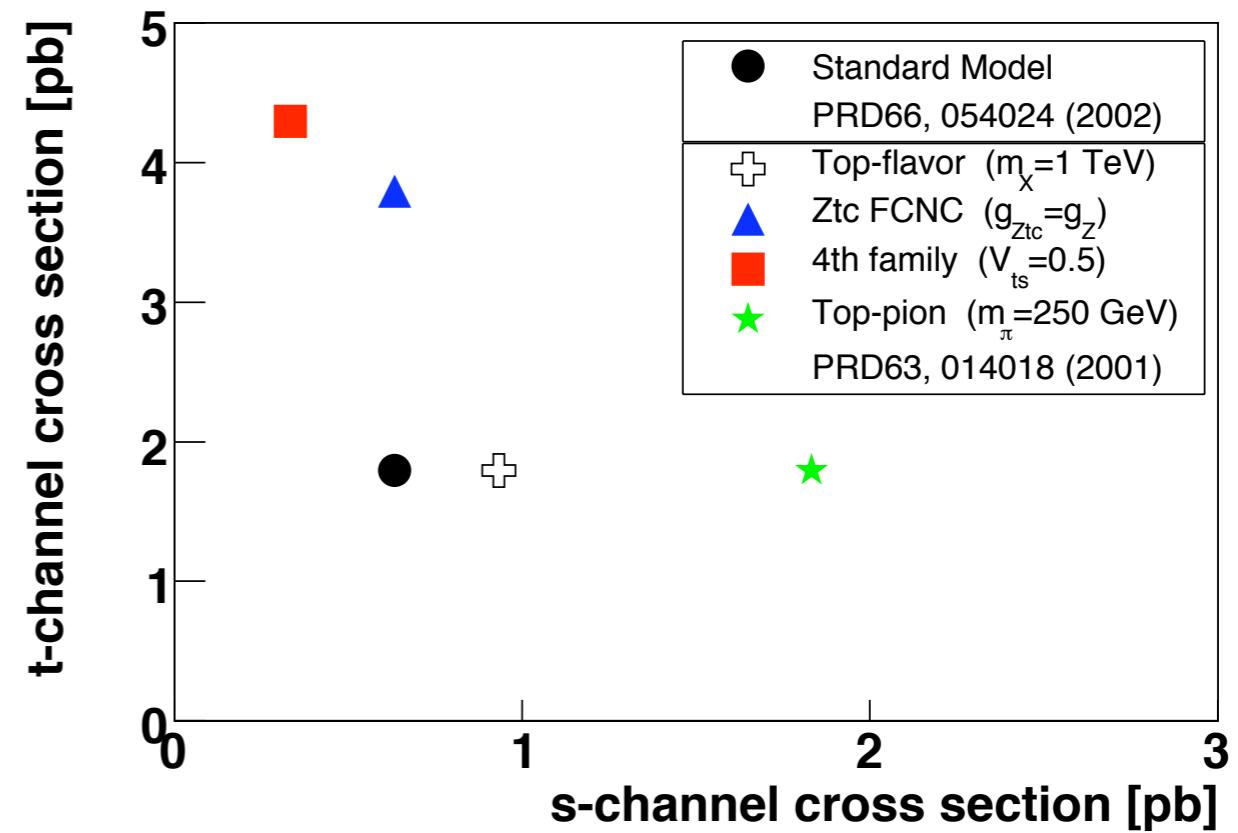
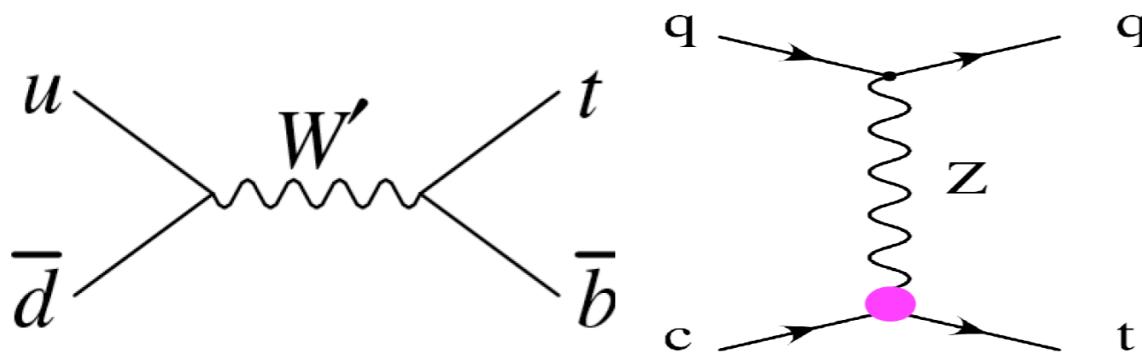


- ❖ Test 3x3 CKM Unitarity

## ◆ Sensitive to new physics

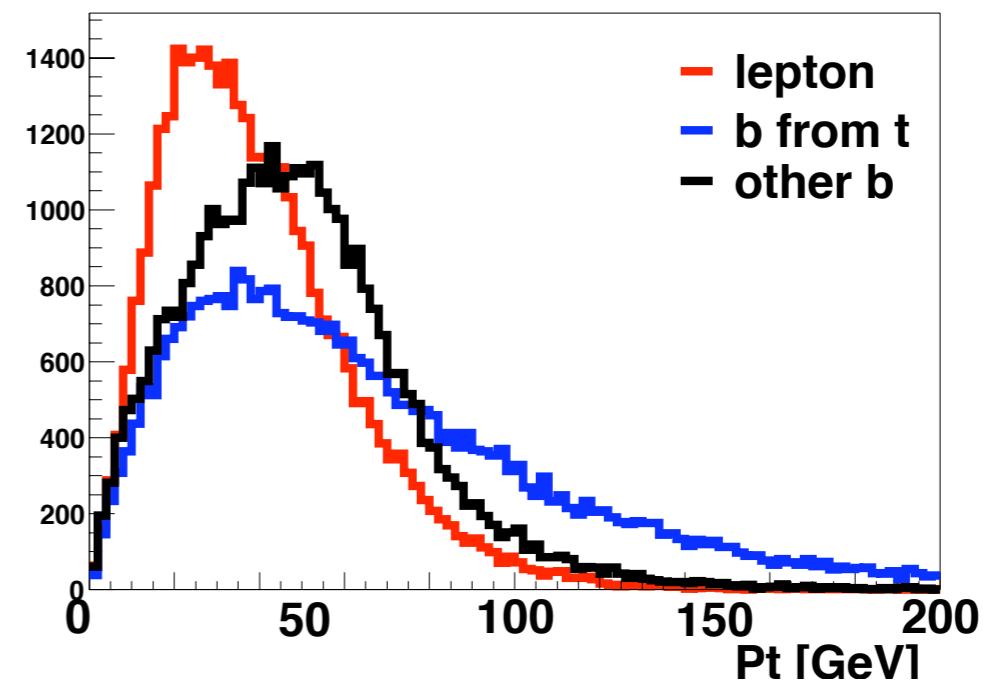
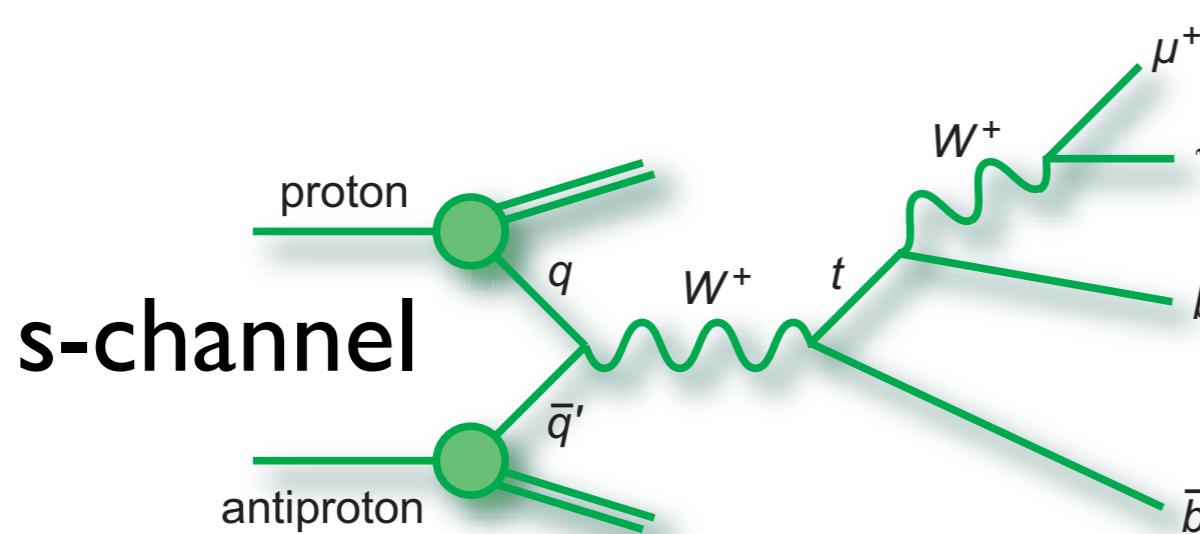
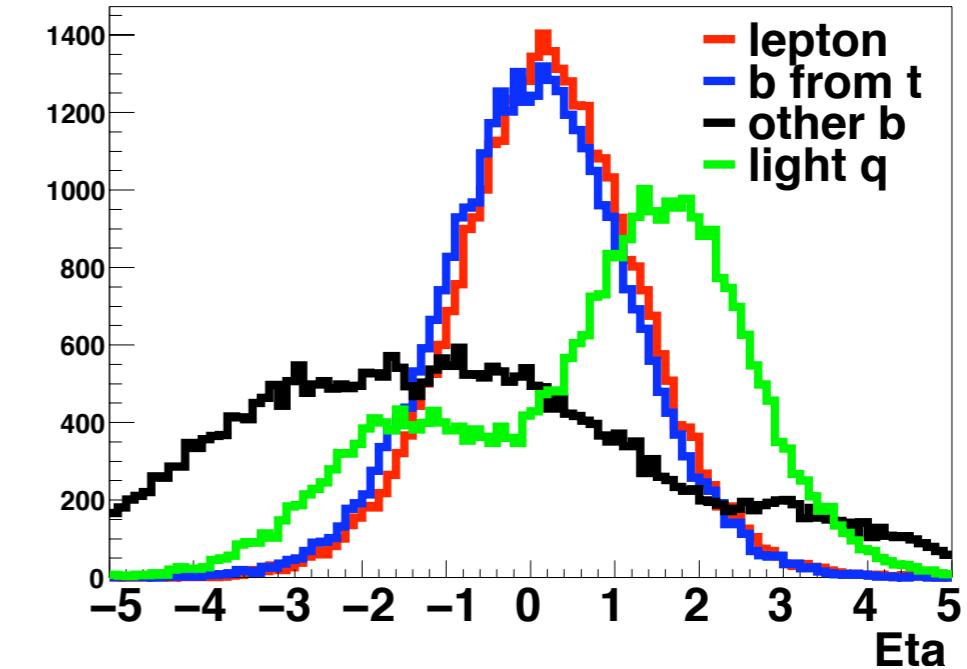
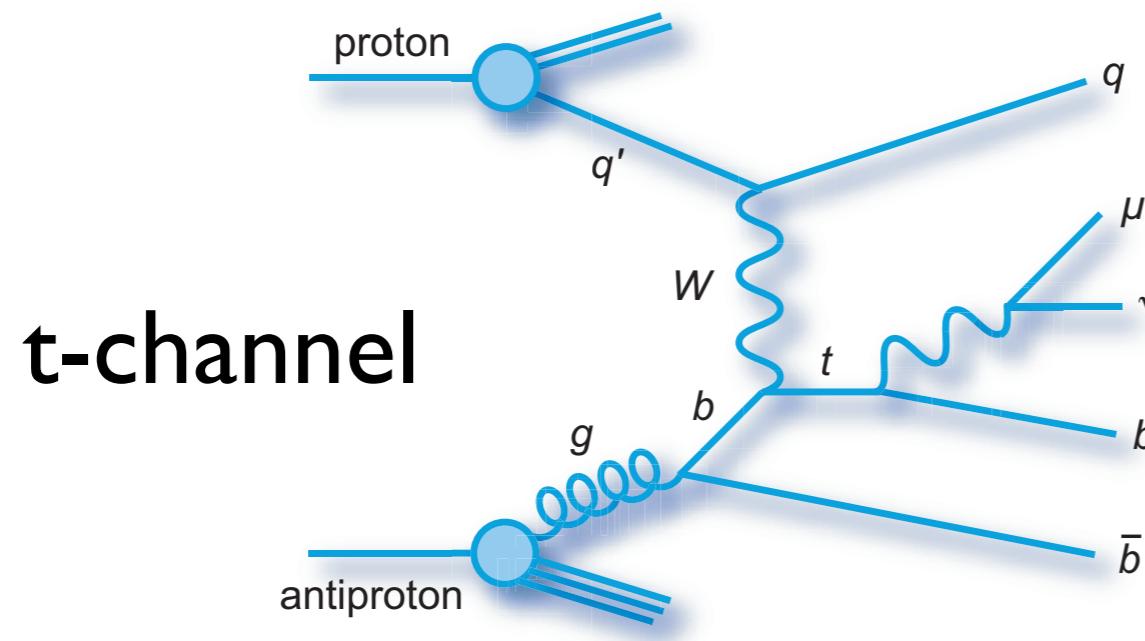
- ❖ s-channel: heavy charged resonances + 4th family

- ❖ t-channel: FCNC + 4 family



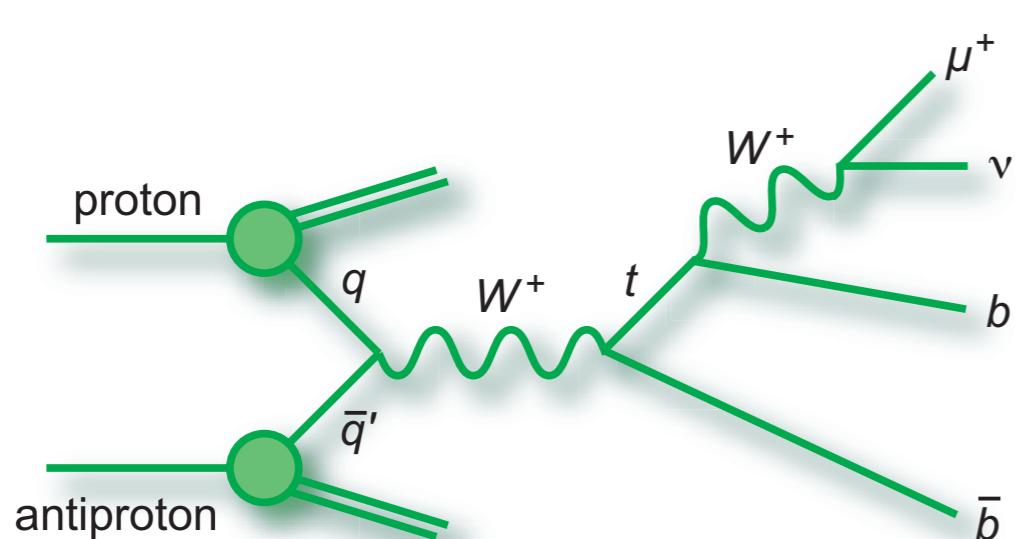
# What Does Single Top Look Like?

- ◆ We use a modified version of CompHEP to model our signal



# Event Topology & Selection Cuts

- ◆ We want to select events with a similar final state as single top
  - ❖ Select W+jets events ( $t \rightarrow Wb$ )

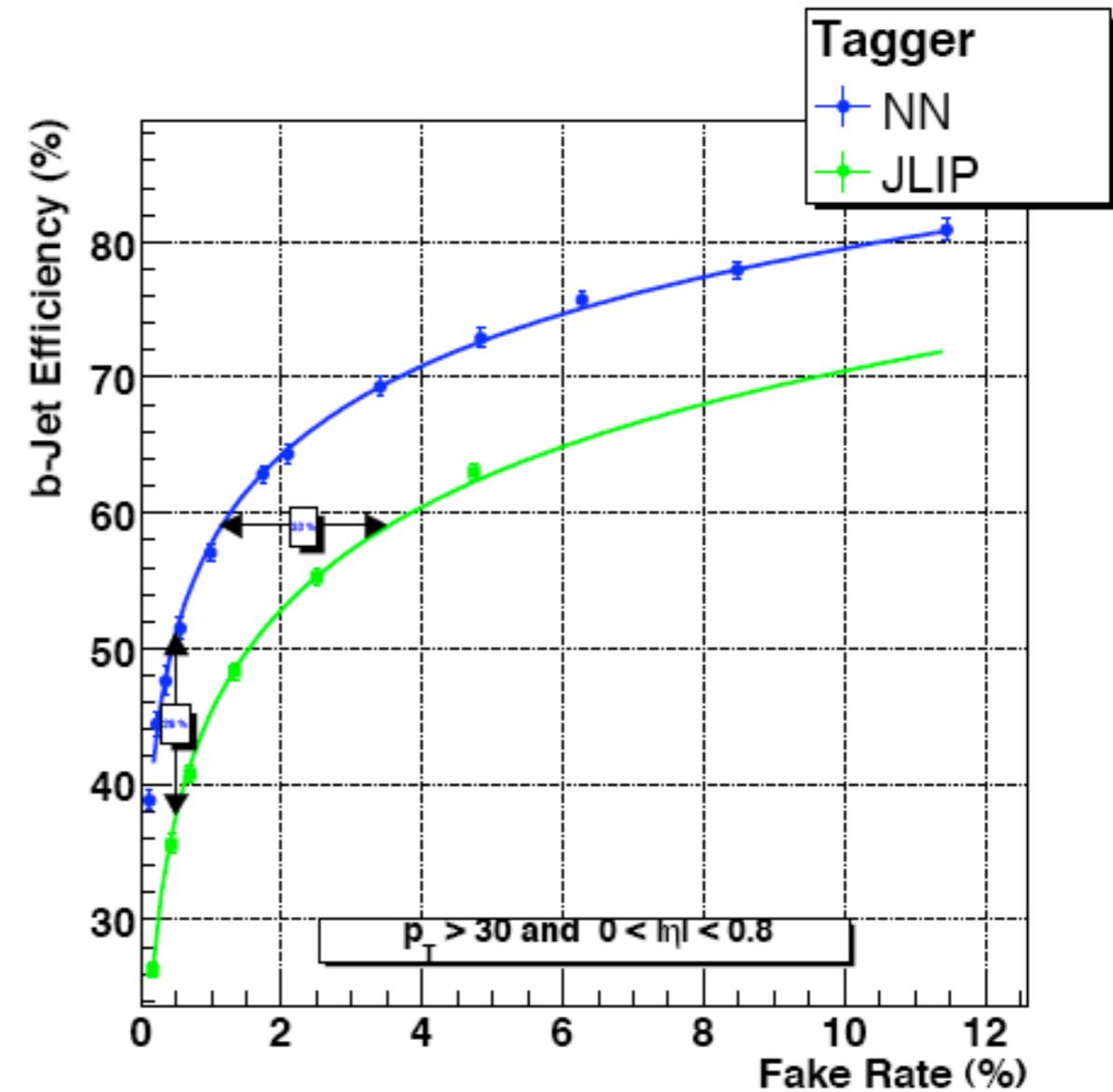


- ❖ 1 isolated lepton with  $p_T > 15 \text{ GeV}$
- ❖ Missing  $E_T > 15 \text{ GeV}$
- ❖ 2 jets with  $p_T > 15 \text{ GeV}$
- ❖ Use forward jets ( $|\eta| < 3.4$ ) for higher t-channel acceptance

- ◆ After selection cuts the main backgrounds are:
  - ❖  $W/Z + 2\text{-}4 \text{ jets}$ :  $\sigma_{W+2\text{jets}} \sim 1 \text{ nb} = 1000 \times \sigma_{\text{single top}}$
  - ❖ Top pair production:  $\sigma_{t\bar{t}} \sim 7 \text{ pb}$ , no top quark separation power
  - ❖ Muons from heavy flavor decays:  $\sigma_{bb} \sim 60 \text{ mb}$ , mostly muons inside jets

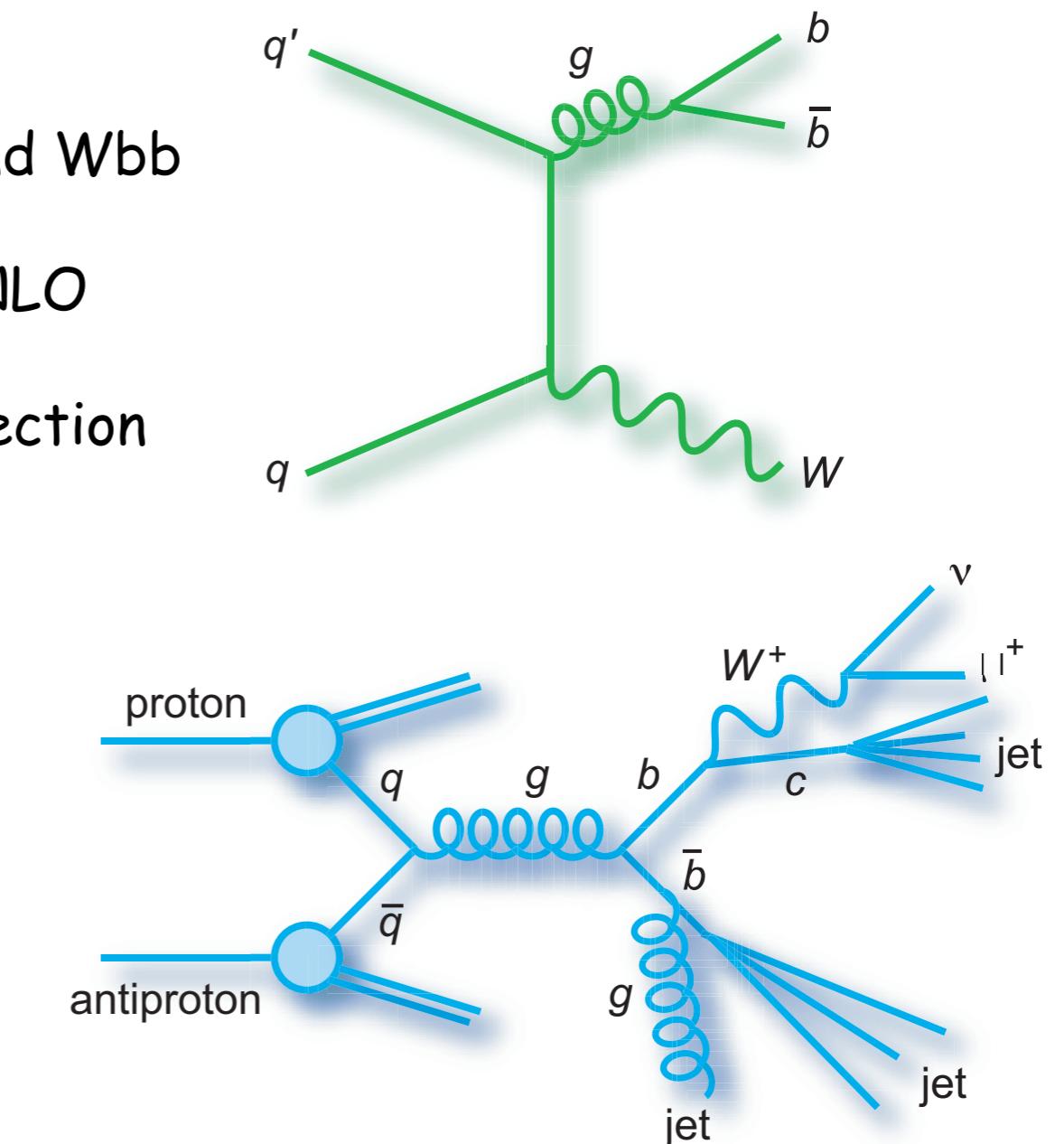
# Neural Network B-Tagging

- ◆ After selection cuts we still have overwhelming W+jets background
- ◆ Since our final state has  $\geq 1$  b quarks we can use b-tagging to improve signal to background
  - ❖ Before b-tagging, S:B  $\sim 1:200$
  - ❖ After b-tagging S:B  $\sim 1:20$
- ◆ DØ uses a neural network tagger
  - ❖ Train NN on light quarks sample as background and b quark sample as signal
  - ❖ Uses more information than previous taggers thus has more separation power (shown right)

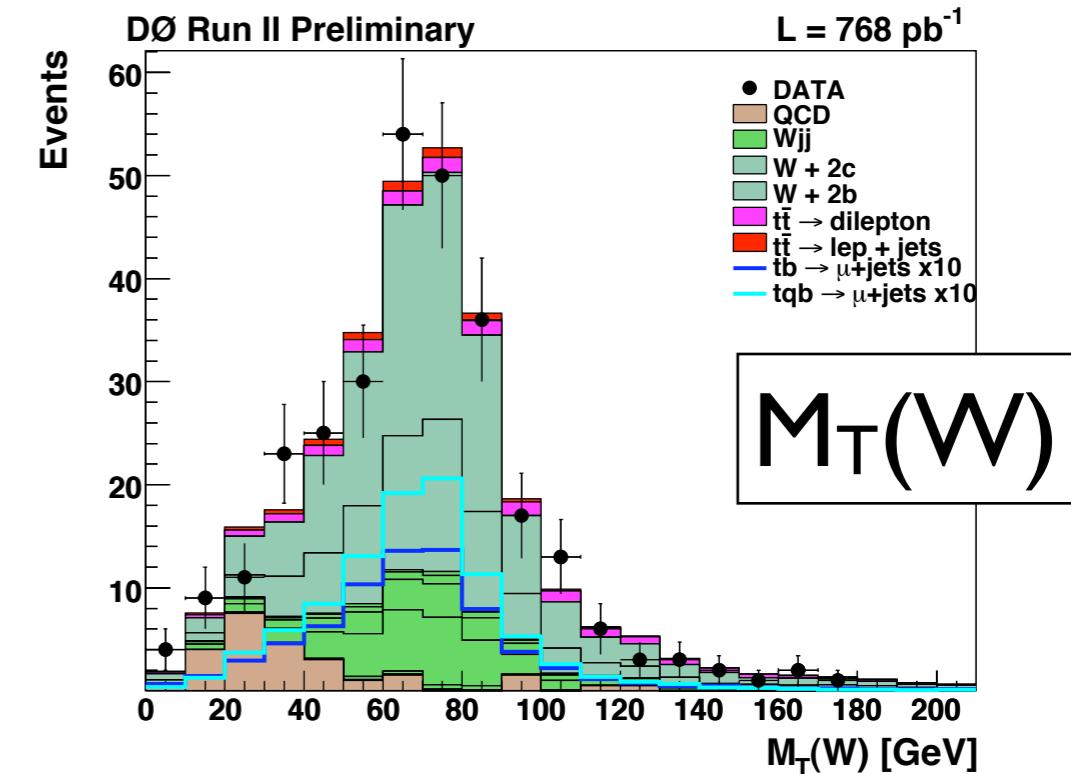
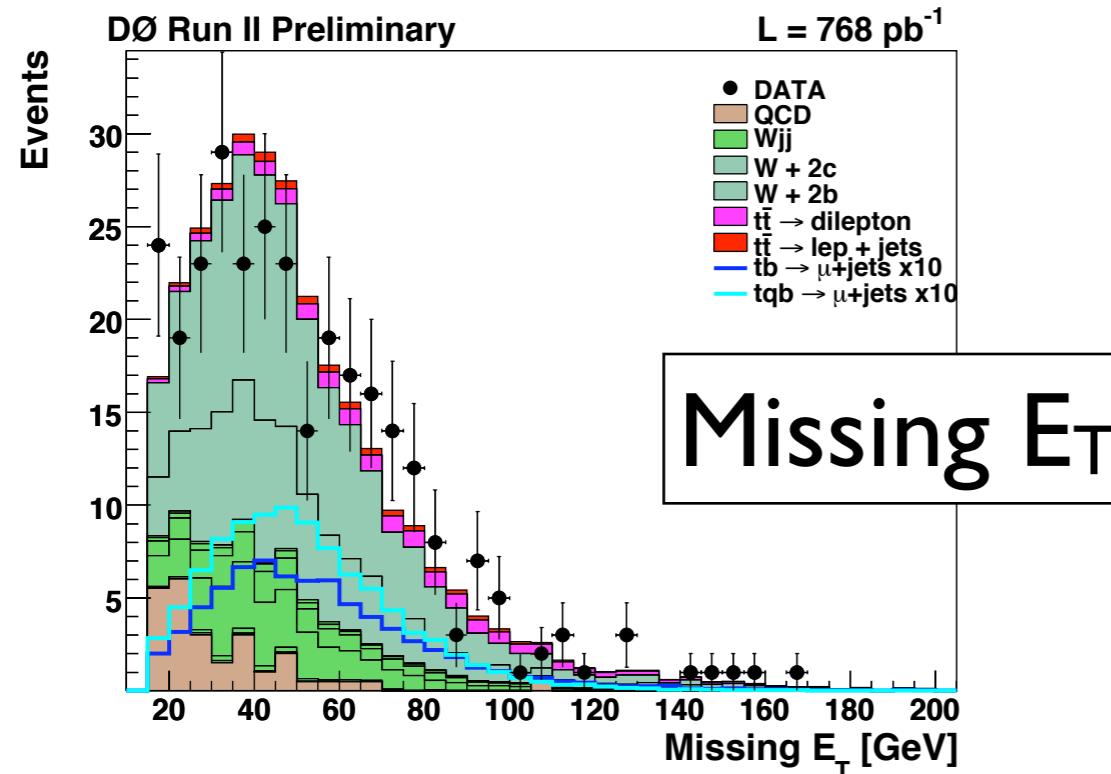
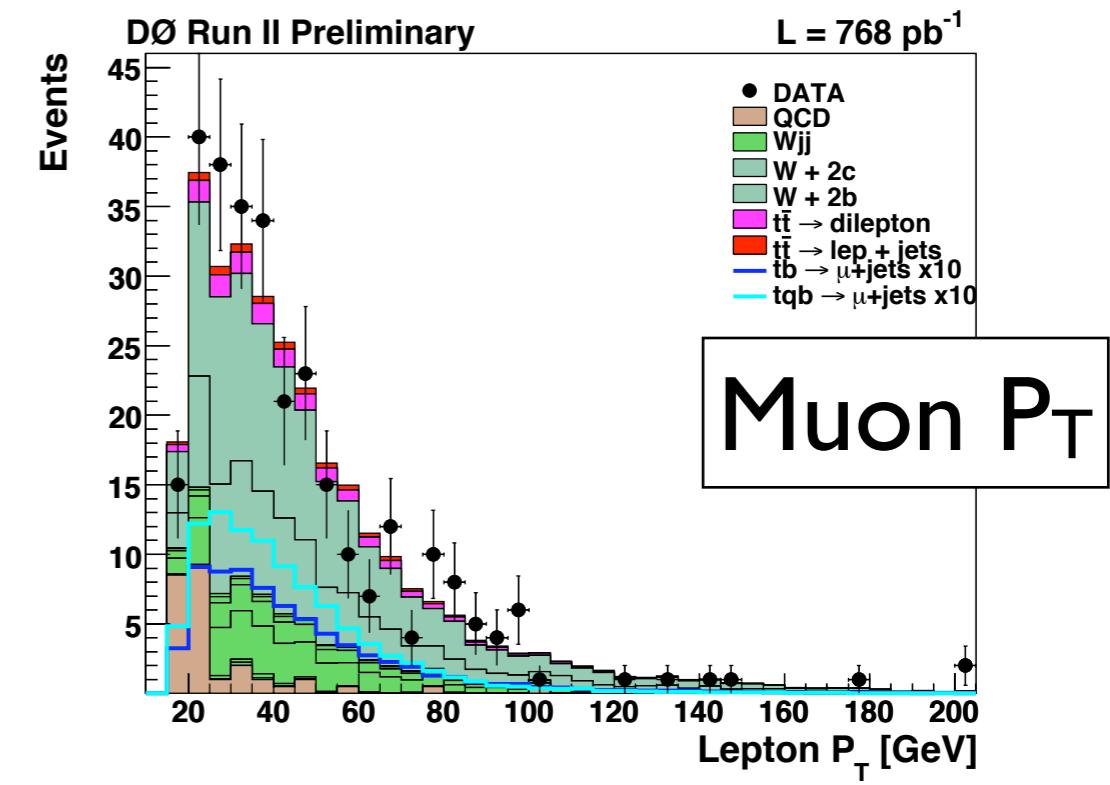
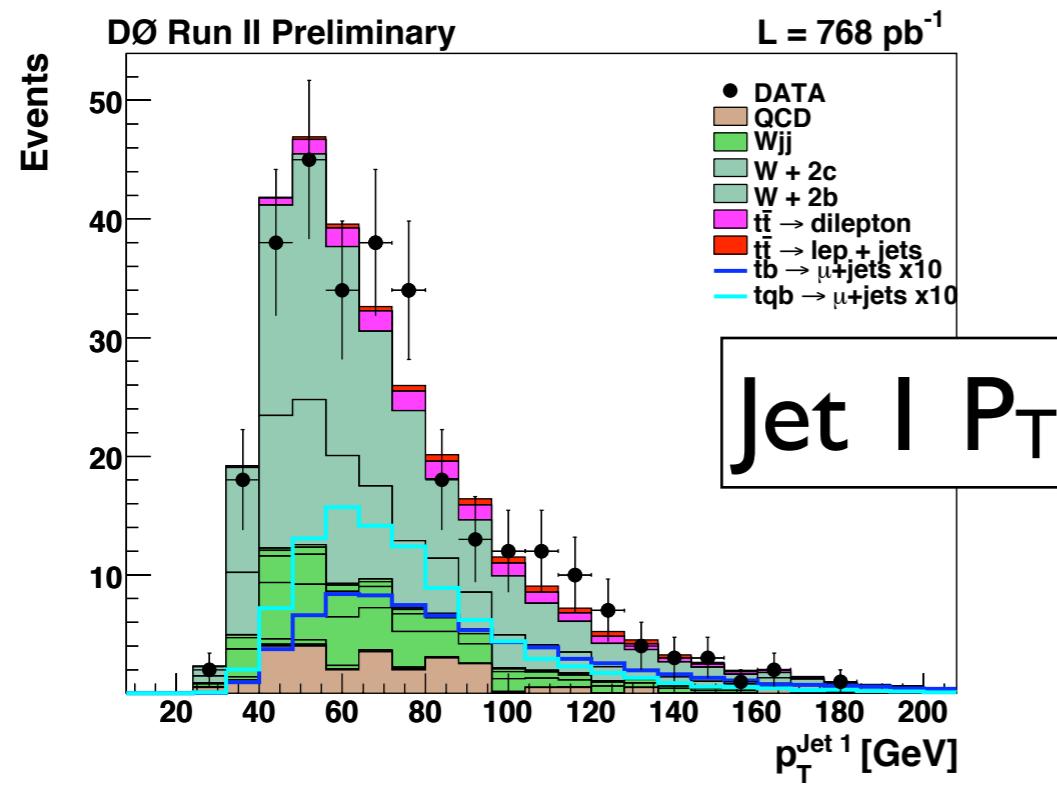


# Background Modeling

- ◆ Major backgrounds are: W+jets, ttbar, and muons from heavy flavor
- ◆ W+jets / ttbar
  - ❖ Use Alpgen for ttbar, Wjj, Wcc, and Wbb
  - ❖ Flavor fractions (k-factors) from NLO
  - ❖ ttbar normalized to theory cross section  
W+jets normalized to data
- ◆ Heavy Flavor (QCD)
  - ❖ Difficult to model in MC because background can result from either physics or detector effects
  - ❖ Modeled using data
- ◆ Normalization: Data = W+jets + ttbar + QCD (pre-tagging)



# Data / Background Comparison (Muon Channel)



# The Road To Discovery

- ◆ After tagging we have a signal to background ratio of  $\sim 1:20$
- ◆ Limits with previous  $370 \text{ pb}^{-1}$  analysis using a likelihood discriminant

$$\sigma_s^{95} < 5.0 \text{ pb}$$

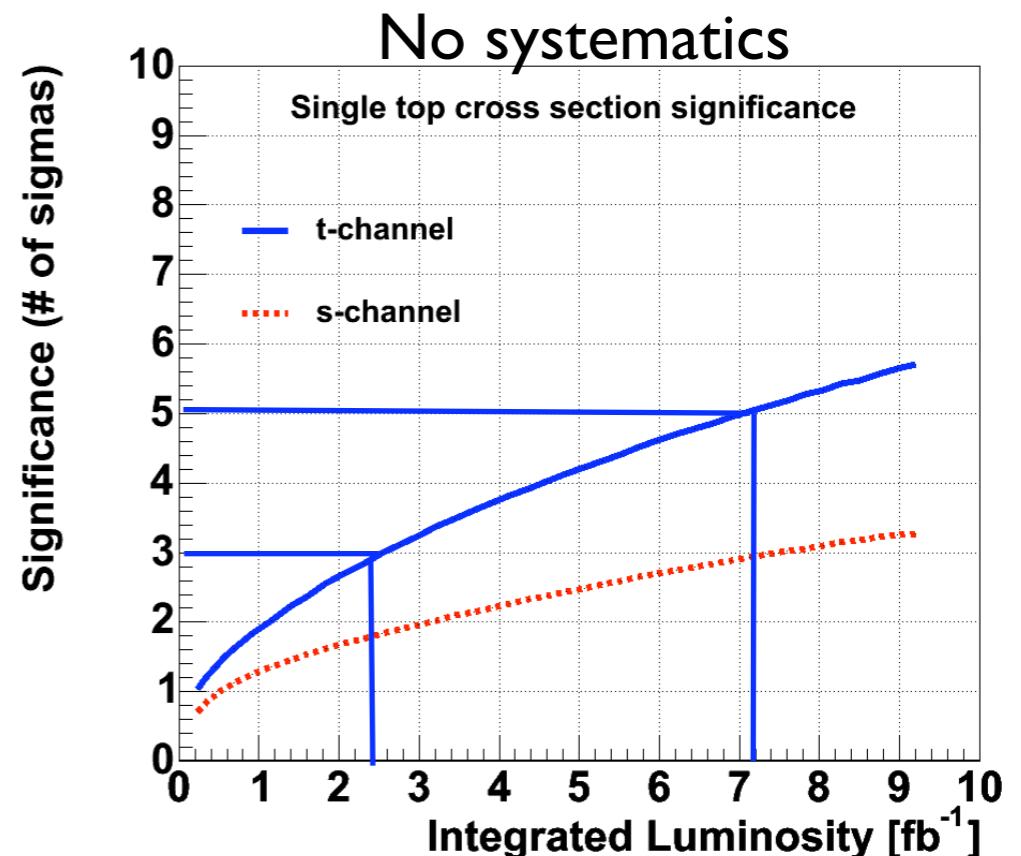
$$\sigma_t^{95} < 4.4 \text{ pb}$$

- ◆  $1 \text{ fb}^{-1}$  current analysis we have:

- ❖ Improved b-tagging
- ❖ New calorimeter calibration
- ❖ Improved jet energy scale

- ◆ I will tell you about my thesis work using the matrix element technique

- ❖ In collaboration with Aurelio Juste (FNAL), Jovan Mitrevski (Columbia), John Parsons (Columbia), and Gordon Watts (Washington).



# Matrix Element Technique

- ◆ Idea: Reconstruct events to the parton level and weight events using the differential cross section for signal and background processes.
- ◆ The probability density that an event,  $\vec{y}$ , to occur from process S:

$$P_S(\vec{y}) = \frac{1}{\sigma_S} d\sigma_S(\vec{y}) \quad \sigma_S = \int d\sigma_S(\vec{y})$$

- ❖ where the differential cross section for a hadron-hadron collision is defined as the hard scatter cross section summed over initial flavor states

$$d\sigma_S(\vec{y}) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1) f_j(x_2) d\sigma_{hs}(\vec{y})$$

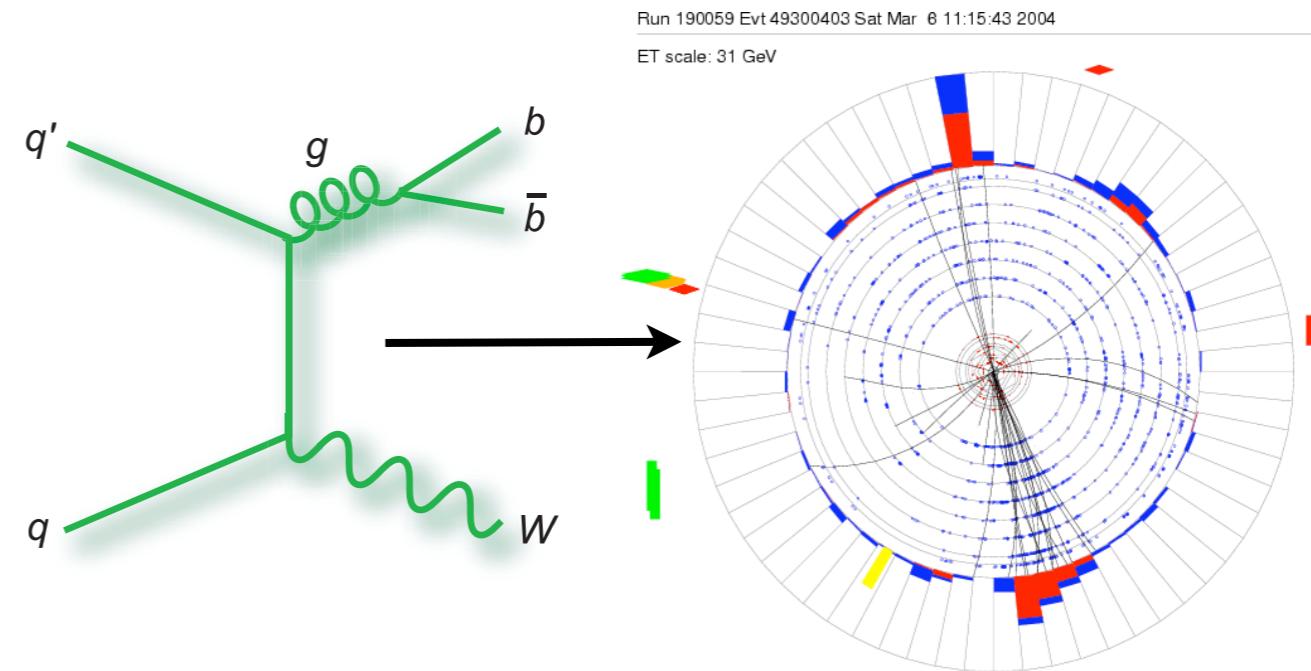
- ❖ with the hard scatter cross section defined as

$$d\sigma_{hs}(\vec{y}) = \frac{2\pi^4 |\mathcal{M}_S(\vec{y})|^2}{4\sqrt{(q_1 q_2)^2 - m_1^2 m_2^2}} d\Phi(\vec{y})_4$$

- ◆ This requires that we compute the initial/final state 4-vectors

# Evaluating the Matrix Element

- ◆ To evaluate  $|M|^2$ , we must have initial/final 4-vectors.
- ❖ We need to know how objects we observe in the detector relate to the original partons.
- ❖ How does the quark energy compare to the corresponding jet energy?
- ◆ Solve this by redefining probability as the product of the differential cross section with the probability to produce  $x$  from  $y$  integrated over  $y$



$$P_S(\vec{x}) \rightarrow P'_S(\vec{x}) = \frac{1}{\sigma'_S} \int \frac{d\sigma_S(\vec{y})}{dy} \times W(\vec{x}, \vec{y}) dy$$

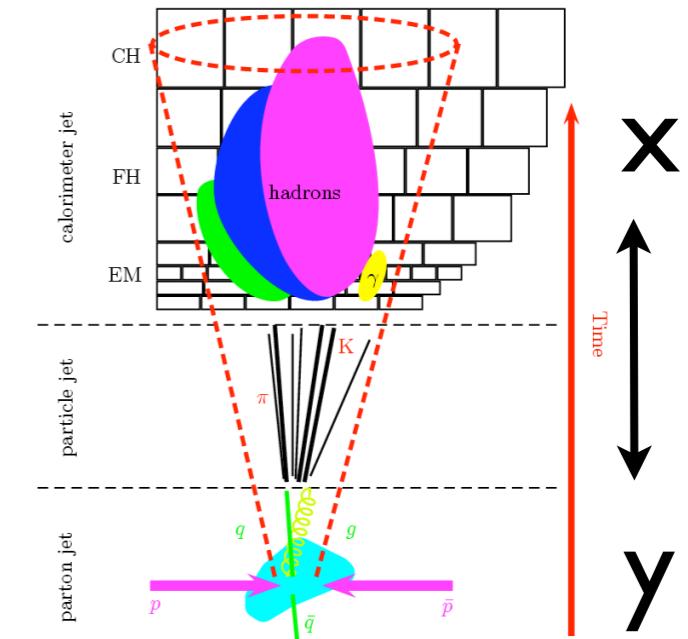
$$\sigma'_S = \int \frac{d\sigma_S(\vec{y})}{dy} \times W(\vec{x}, \vec{y}) \Theta_{\text{cuts}}(\vec{x}) d\vec{y} d\vec{x}$$

- ❖ Where  $x$  is the observed state in the detector and  $y$  is the final state

# Evaluating the Matrix Element cont.

- ◆ Transfer function answers: If I observe  $x$  in the detector, then how likely did it originate as  $y$  in the final state.
- ◆ Assume detector objects are independent.

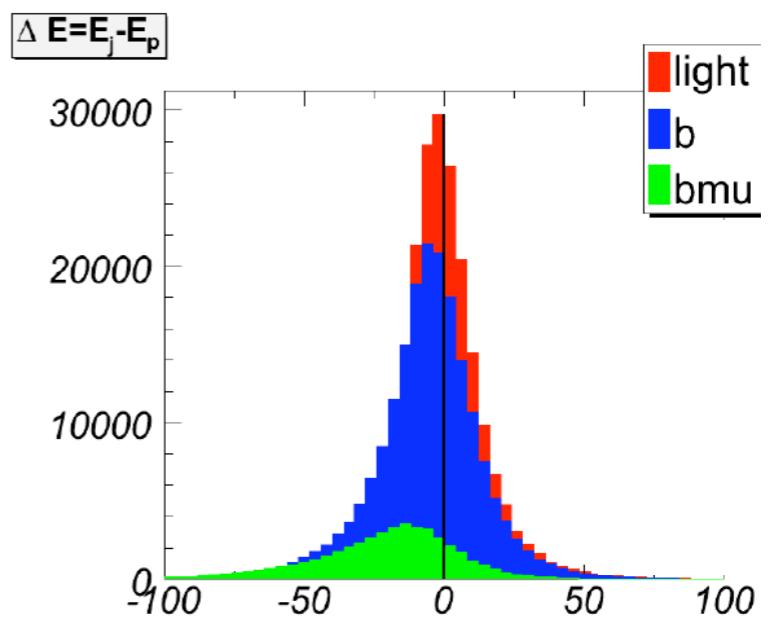
$$W(\vec{x}, \vec{y}) = \prod_i W_i(\vec{x}_i, \vec{y}_i)$$



- ◆ Calorimeter objects have well measured angles

$$W_{\text{jet}}(\vec{x}_{\text{jet}}, \vec{y}_{\text{parton}}) \rightarrow W_{\text{jet}}(E_{\text{jet}}, E_{\text{parton}}) \times \delta(\Omega_{\text{jet}} - \Omega_{\text{parton}})$$

- ◆ Require one jet per parton
  - ❖ 2 jet events require two parton,  
3 jet events require three partons, etc..
- ◆ Calculated for different jet flavors

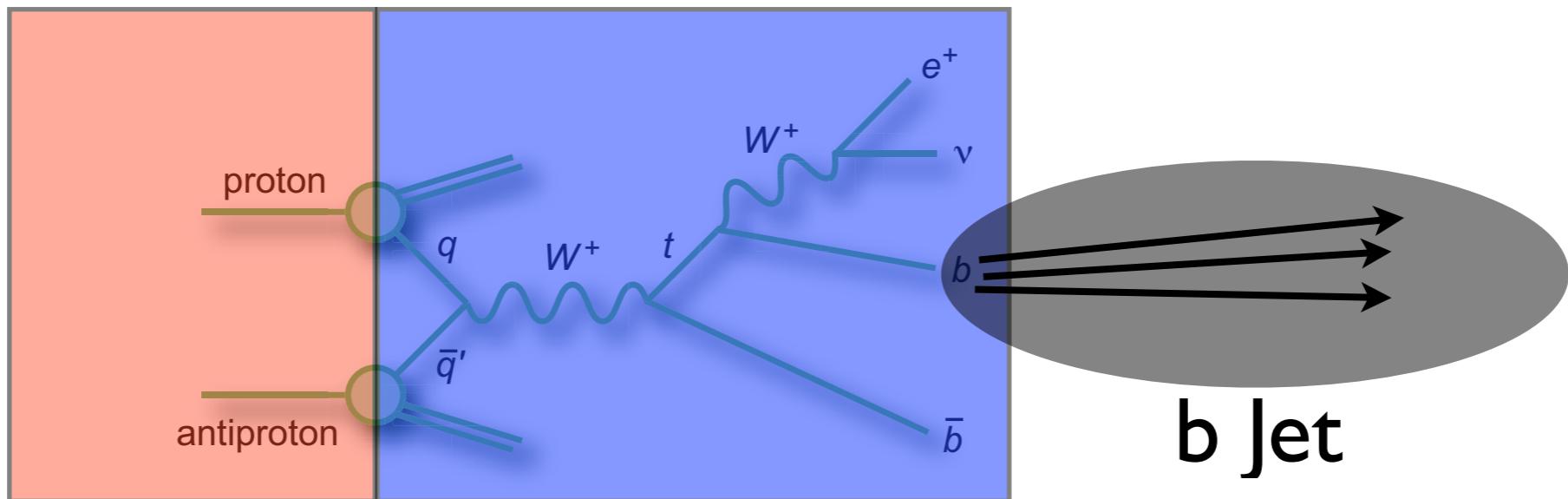


# Evaluating the Matrix Element cont.

- ◆ We now know how to go backwards from detector to final state.
- ◆ To reconstruct the event we need to integrate over the 4 unknown independent variables.
- ❖ 24 unknowns: -6 mass, -6 Angles, -4 beam axis, -4 total momentum and energy = 4

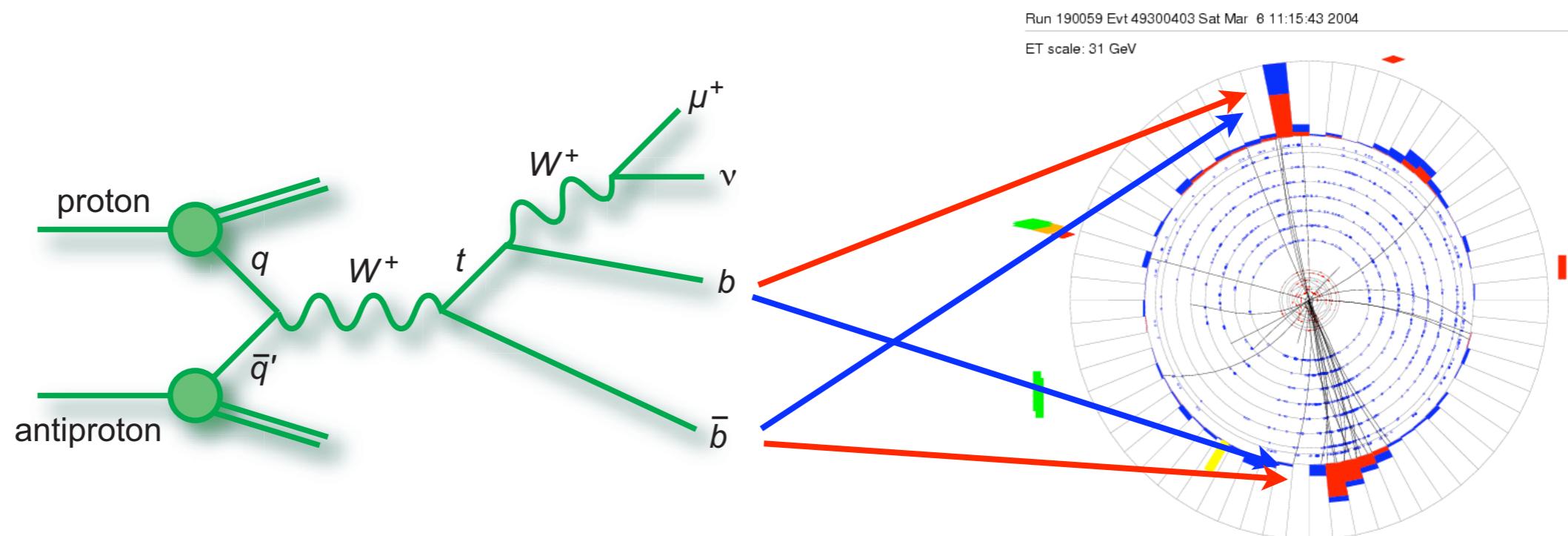
$$P_S(\vec{x}) = \frac{1}{\sigma_S} \int f(q_1; Q) dq_1 f(q_2; Q) dq_2 \times \frac{2\pi^4 |\mathcal{M}_S(\vec{y})|^2}{4\sqrt{(q_1 q_2)^2 - m_1^2 m_2^2}} \Phi(\vec{y}) dy \times W(\vec{x}, \vec{y})$$

Vegas      CTEQ6.1 LO      Madgraph      MC



# Jet-Parton Assignment

- ◆ Everything so far has assumed we can correctly assign each jet with the originating final state parton.



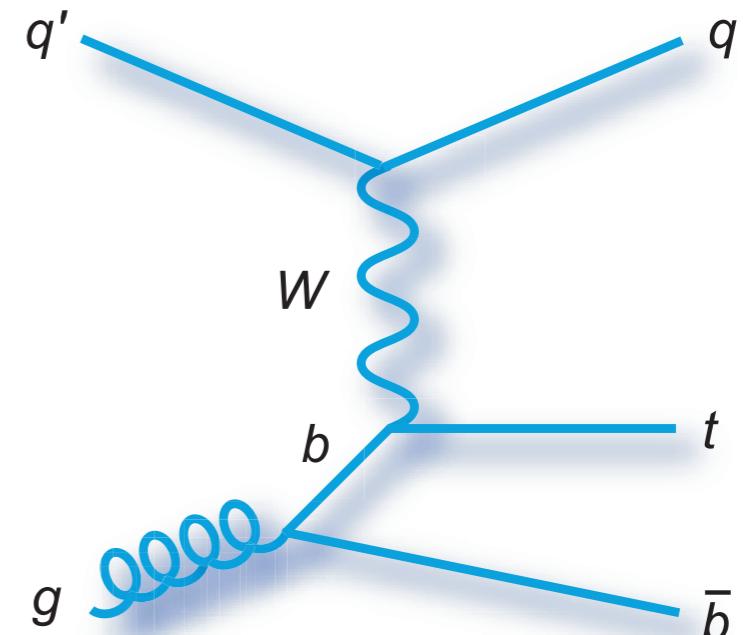
- ◆ Since we do not know this information we must sum over each assignment.

$$P_S(1,2) = \alpha P_S(1 \rightarrow 1, 2 \rightarrow 2) + \beta P_S(2 \rightarrow 1, 1 \rightarrow 2)$$

- ❖ If there is no knowledge of the correct assignment, then  $\alpha = \beta = 0.5$

# Improving Separation Power

- ◆ We can use btagging to help assign b jets to b quarks.
- ◆ Idea: We are likely to assign a tagged jet to a b quark and very likely to assign an untagged jet to a light quark.
- ◆ Example: single tagged t-channel:  $u\bar{b} \rightarrow t \rightarrow W b d$ :
  - ❖ 1). b-tag b quark jet from top and not tag down quark jet  
 $\alpha = \epsilon_b \times (1 - \epsilon_l) \sim 0.6$
  - ❖ 2). b-tag down quark jet and not tag b quark jet from top  
 $\beta = (1 - \epsilon_b) \times \epsilon_l \sim 0.005$



$$P_S(\text{bJet}, \text{lJet}) = \alpha P_S(\text{bJet} \rightarrow b, \text{lJet} \rightarrow d) + \beta P_S(\text{bJet} \rightarrow d, \text{lJet} \rightarrow b)$$

# Signal Background Separation

- ◆ Once we have event probabilities we define a discriminant, D, as

$$D(\vec{x}) = \frac{P_{\text{Signal}}(\vec{x})}{P_{\text{Signal}}(\vec{x}) + P_{\text{Background}}(\vec{x})}$$

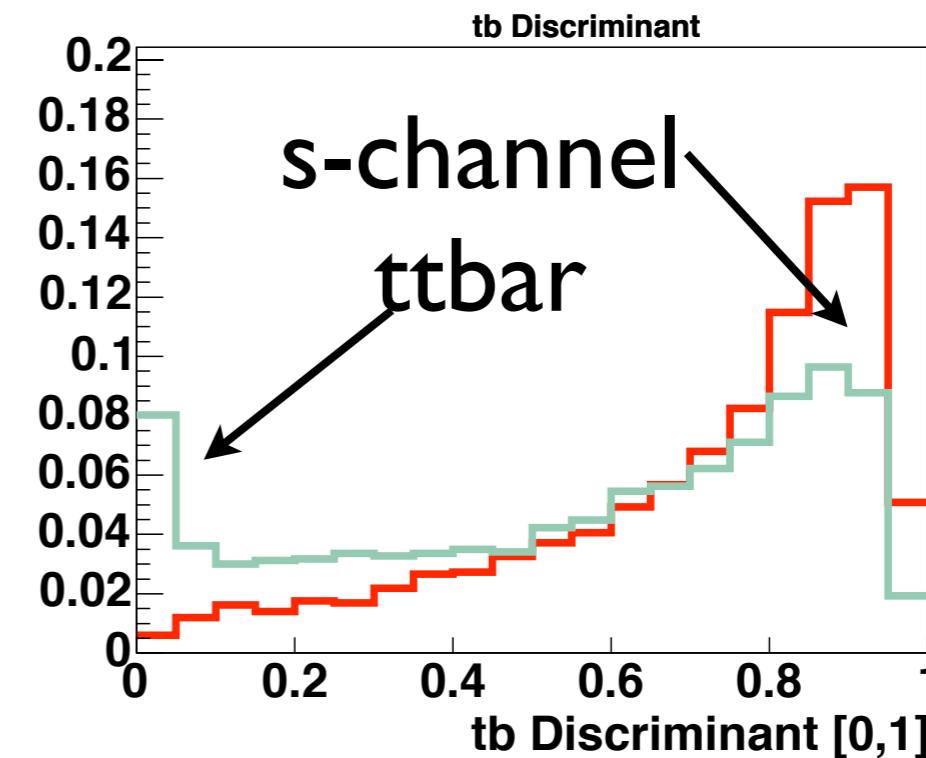
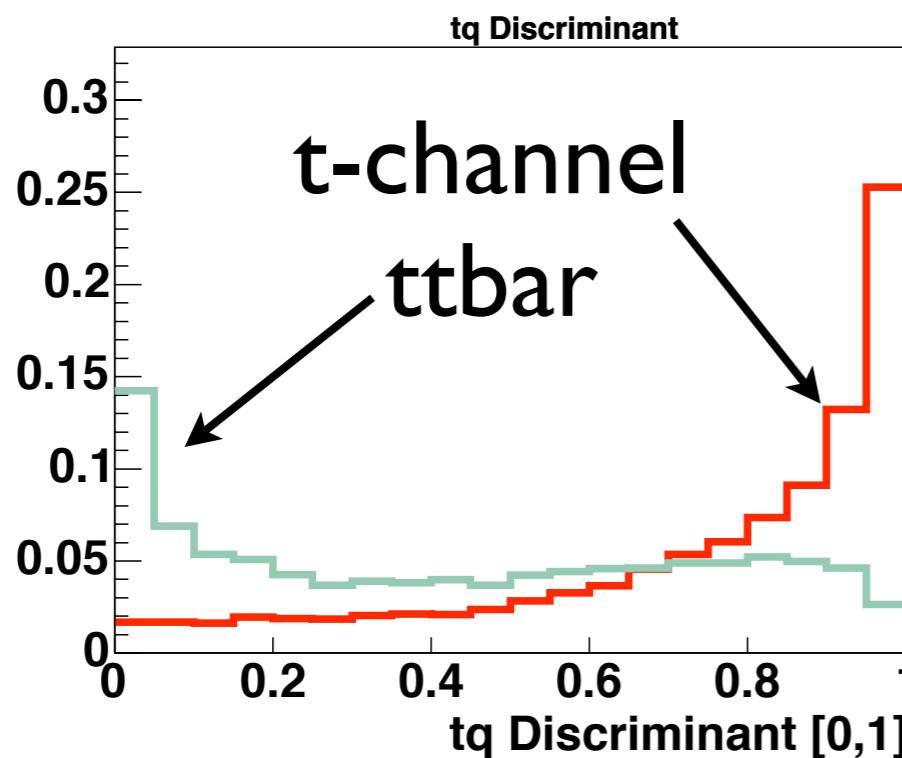
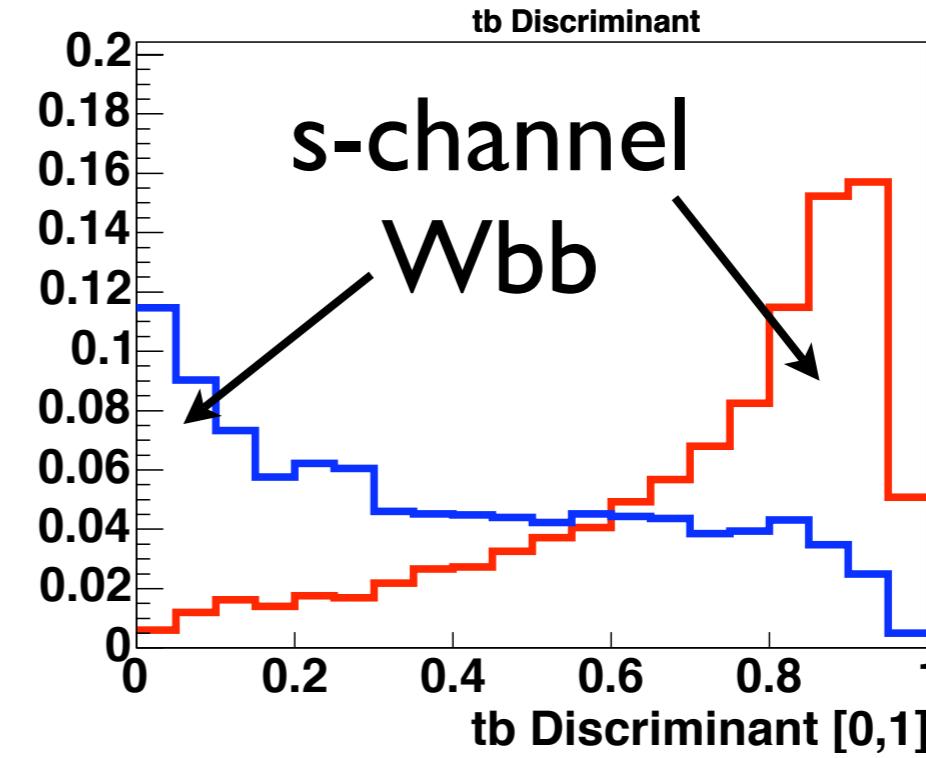
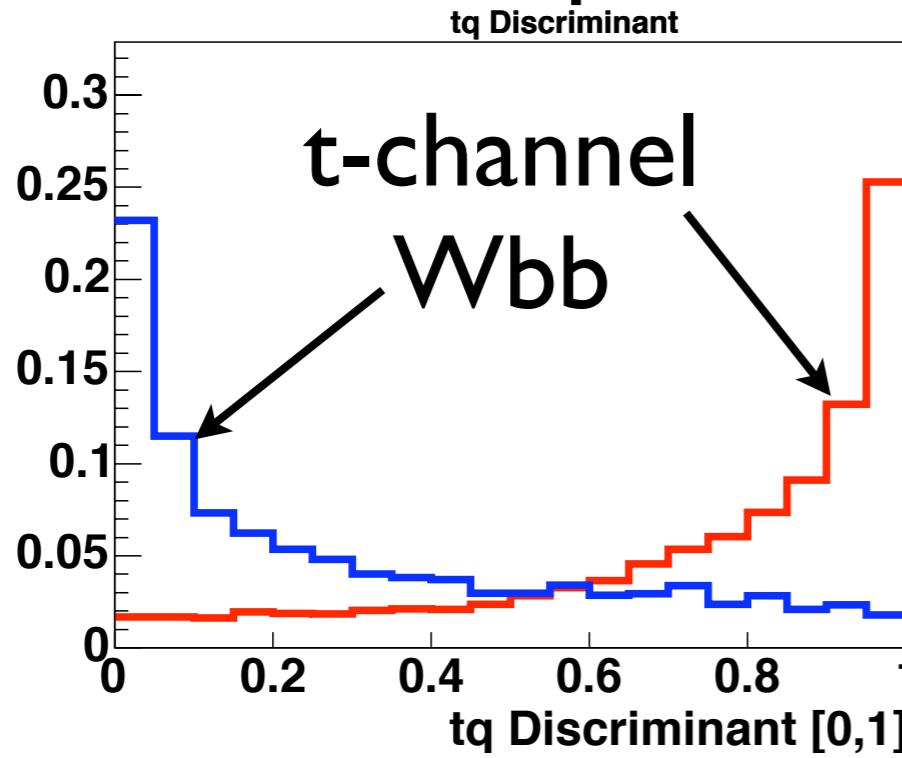
- ◆ We have two signals ( s-channel and t-channel ) and two matrix elements for the background estimate ( Wbb and Wcg ).

$$D_{s|t}(\vec{x}) = \frac{P_{s|t}(\vec{x})}{P_{s|t}(\vec{x}) + c_{Wb\bar{b}}P_{Wb\bar{b}}(\vec{x}) + c_{Wcg}P_{Wcg}(\vec{x})}$$

- ❖ where  $c_{Wb\bar{b}}$  and  $c_{Wcg}$  are the relative fractions of Wbb and Wcg events in our W+jets background.
- ❖ Note: There is no ttbar or QCD matrix element in our discriminant.

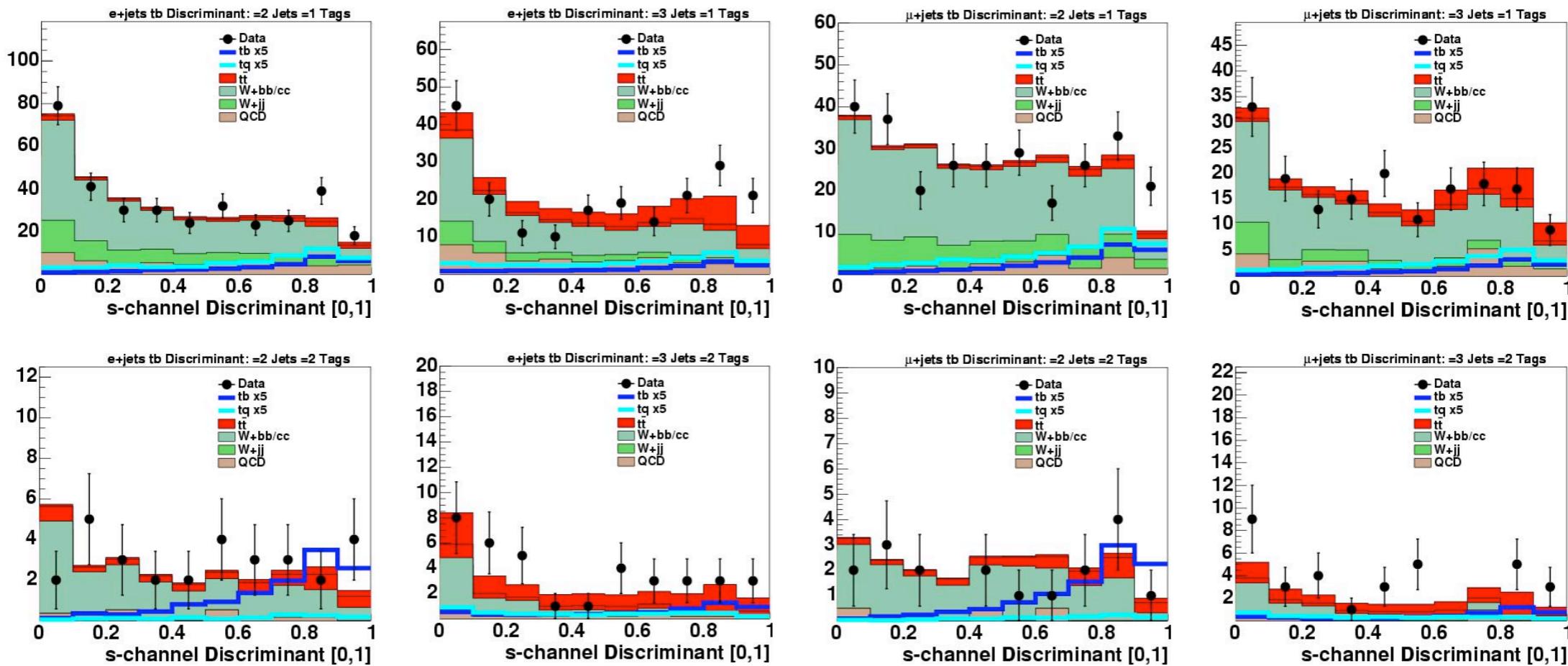
# Discriminant Separation Power

All plots normalized to unit area



# Data/MC Agreement in 8 Channels

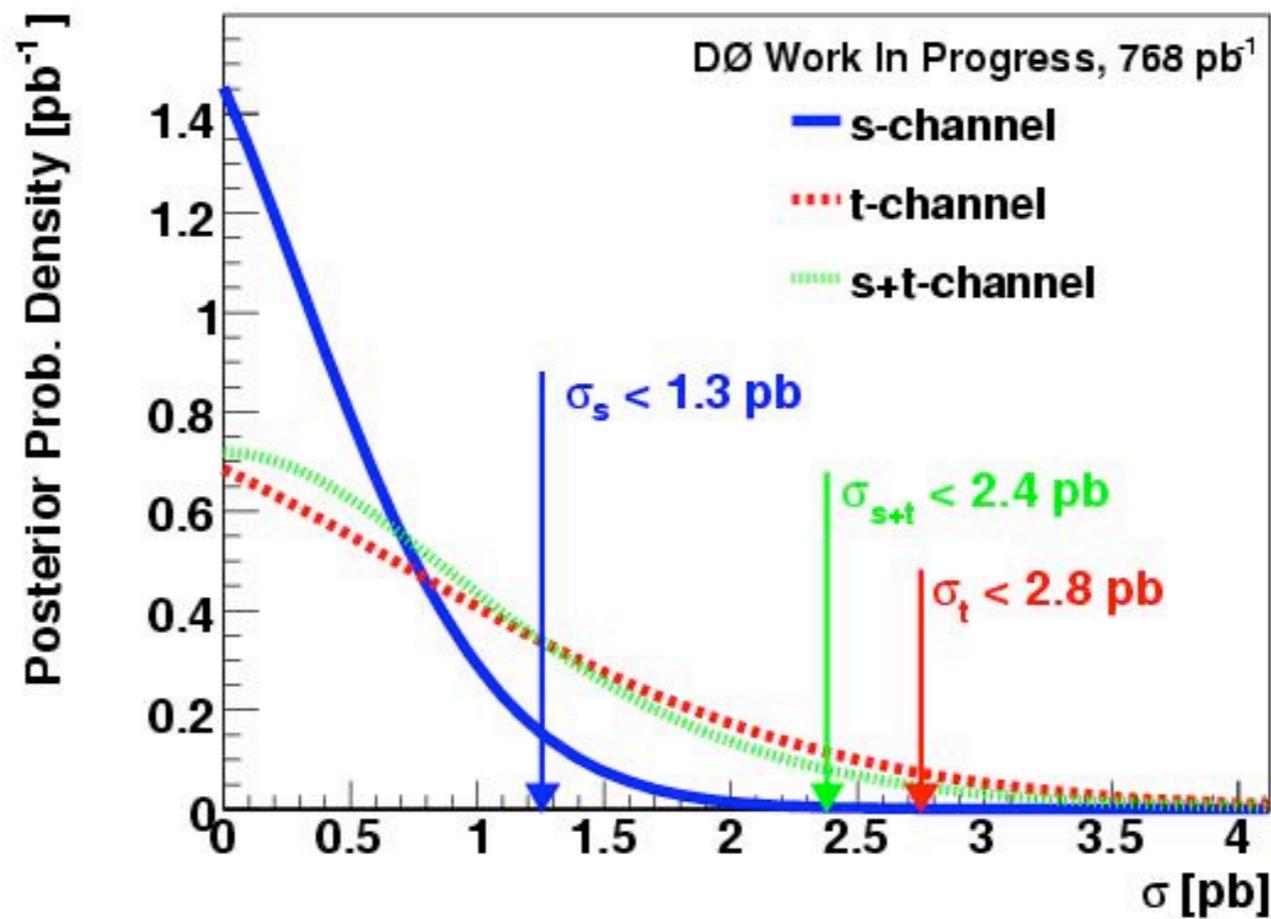
- ◆ There are 8 orthogonal channels for which we compute an s-channel and t-channel discriminant
  - ❖ {2 jets, 3 jets}  $\times$  {electron, muon}  $\times$  {=1 tag, =2 tags} = 8 channels
- ◆ Below: s-channel Discriminant for 8 channels



- ◆ Limits are calculated using a Bayesian statistics with a binned likelihood

# Sensitivity with $\sim 800 \text{ pb}^{-1}$

- ◆ Because we have not done a fully error estimation for our dataset, we are not ready to show limits with observed data.
- ◆ We can calculate the expected limit given our observation equals the background estimate.

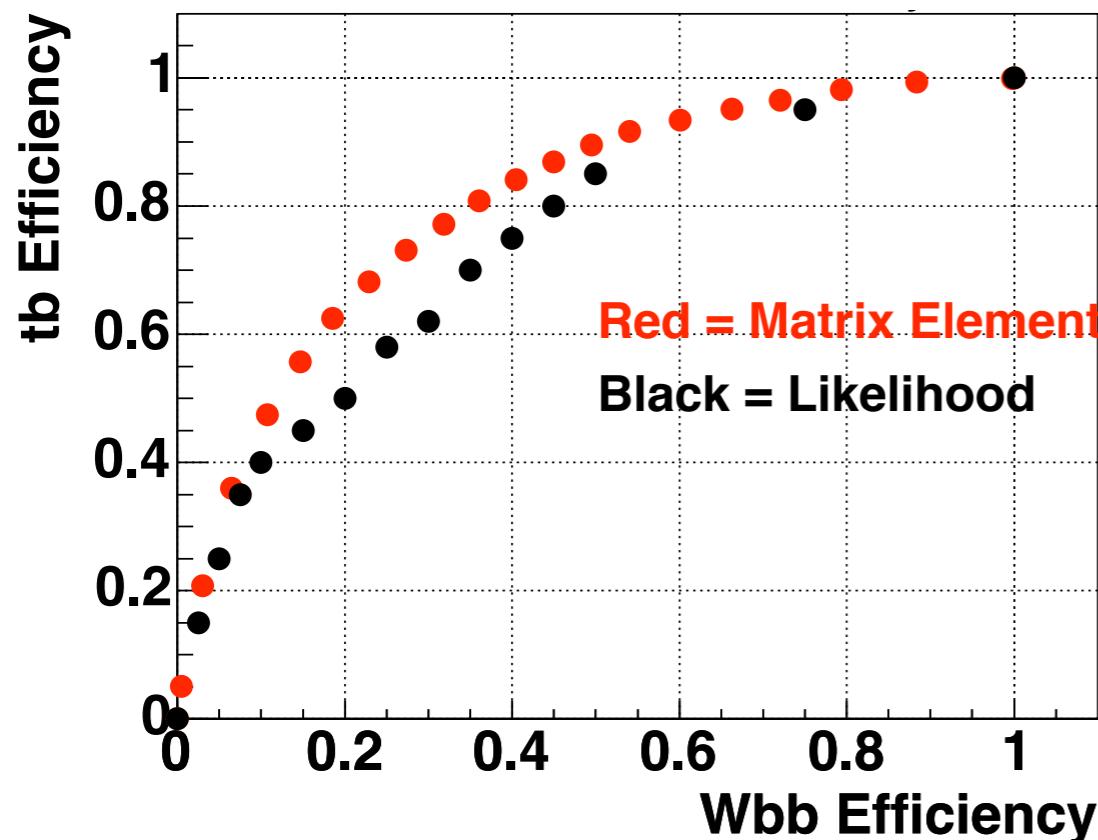


$$\sigma_s = 0.88 \pm 0.07 \text{ pb} \quad \sigma_t = 1.98 \pm 0.21 \text{ pb}$$

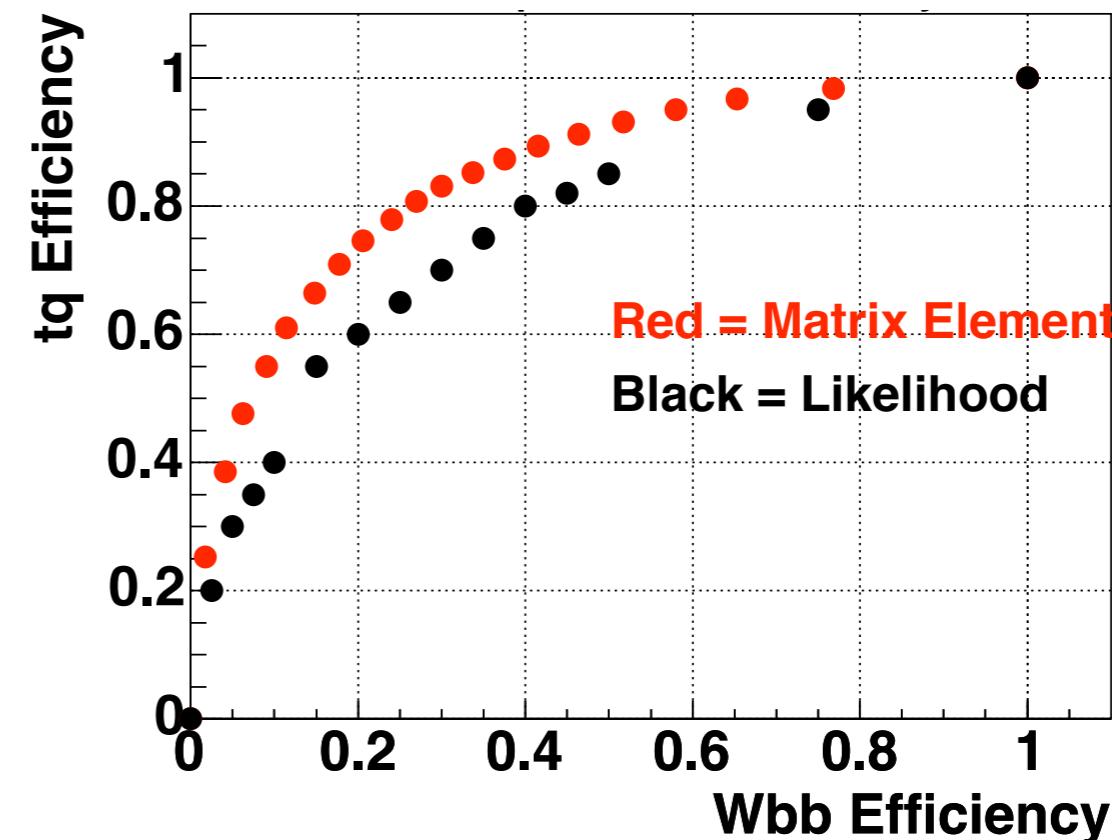
# Comparison with $370 \text{ pb}^{-1}$ Likelihood

- ❖ Have we gained any more separation using matrix elements over using a simple likelihood trained on discriminating variables?
- ❖ YES!

s-channel Discriminant

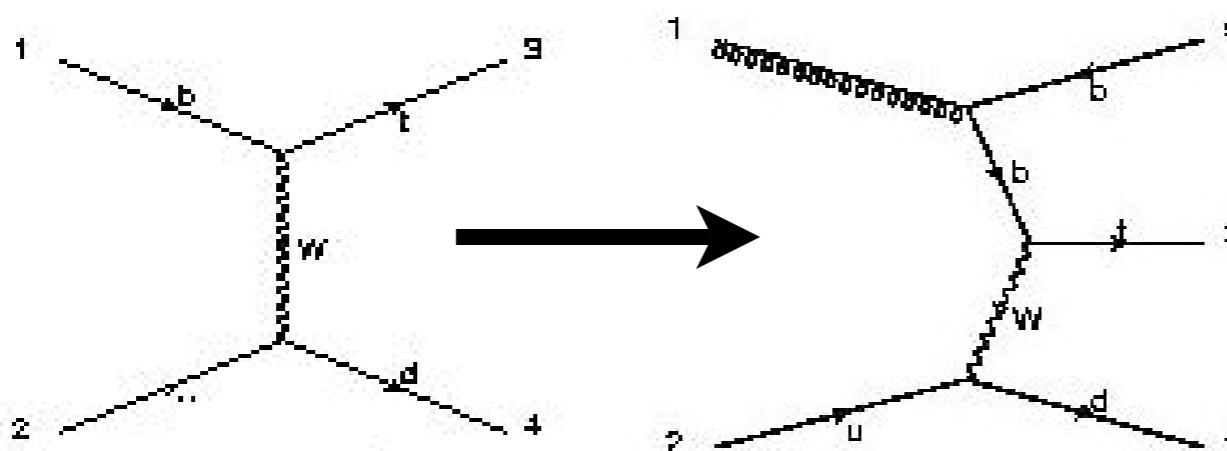


t-channel Discriminant



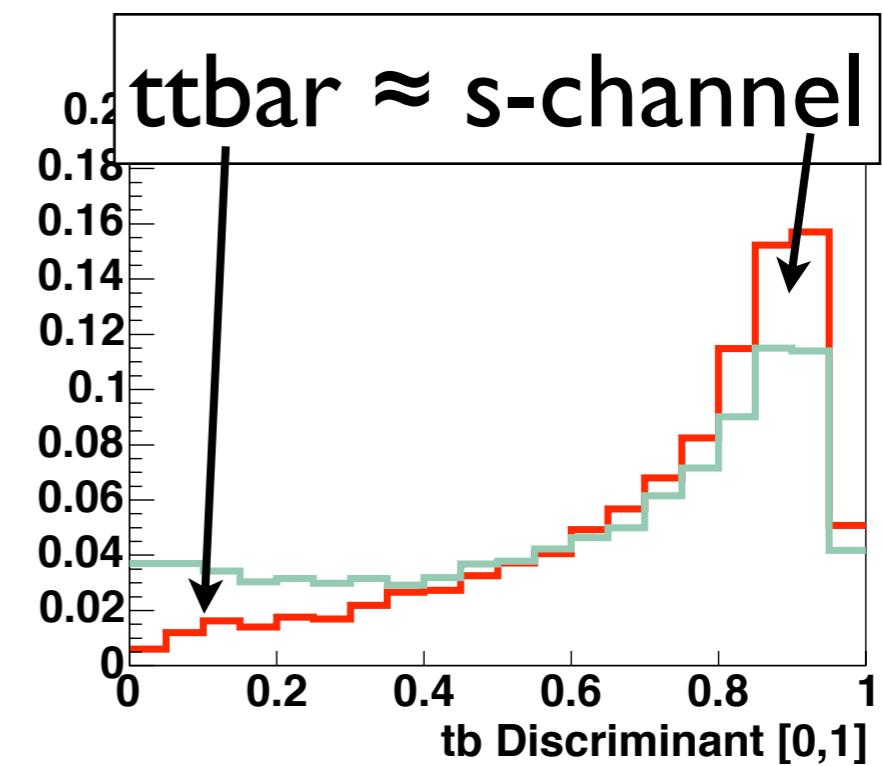
# Improving Our Sensitivity

- ◆ Properly include events with 3 jets
  - ❖ Lots of signal acceptance for t-channel
  - ❖ Need 2->3 matrix elements



	2 Jets	3 Jets
I Tag	27%	13%
2 Tags	20%	11%

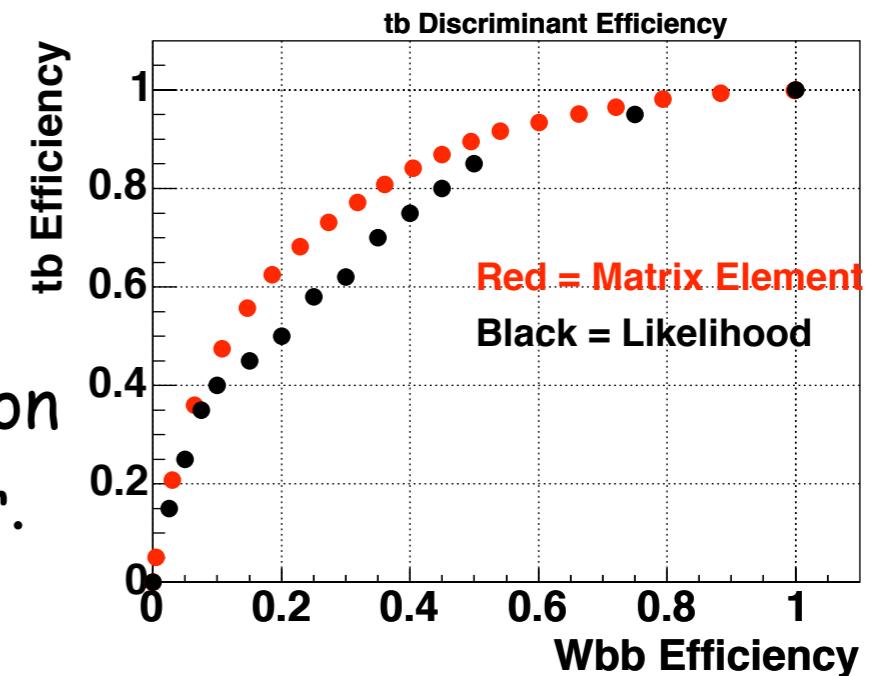
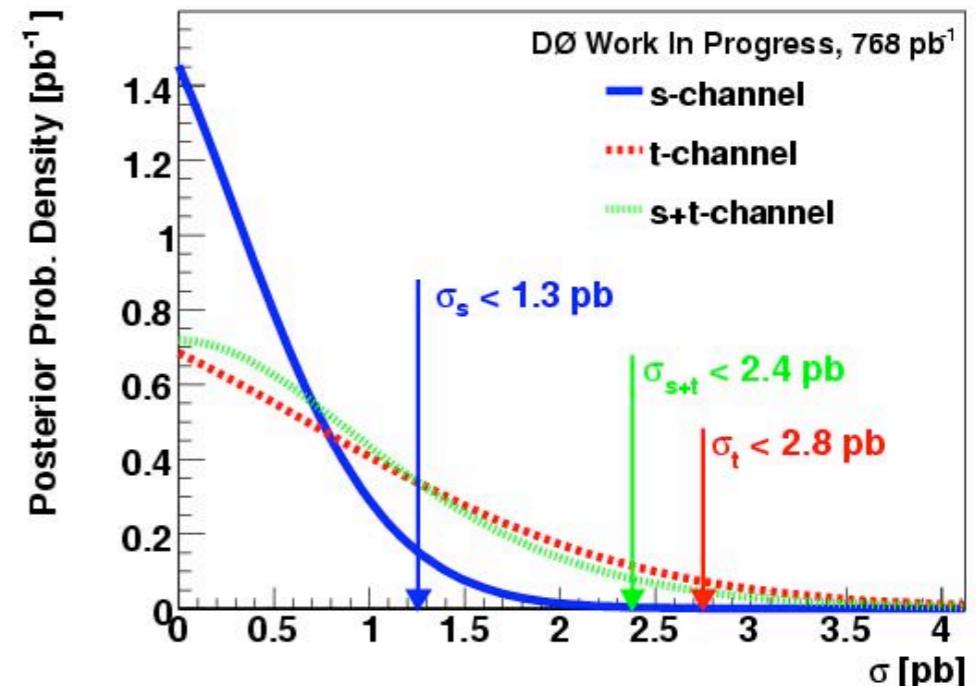
- ◆ Add ttbar matrix element
  - ❖ Can not do 1:1 jet → parton mapping
  - ❖ More important in 3 jet events



# Summary & Outlook

- ◆ DØ has collected over  $1.3 \text{ fb}^{-1}$  of RunII data.  
More than 10x RunI.
- ◆ We have set preliminary limits on s-channel and t-channel single top using  $\sim 800 \text{ pb}^{-1}$ 
  - ❖ s+t expected limit (w/o errors) is below SM prediction
- ◆ Using matrix elements to help separate single top signal from W+jets background has improved our sensitivity.
- ◆ This is a very exciting time at the Tevatron Discovery could be just around the corner.

Stay Tuned...



# **Backup Slides**

# Top quark Electroweak production

Single top production via EW interaction

$$\sigma(t) \sim 2.86 \text{ pb at } \sqrt{s}=1.96 \text{ TeV} \quad (\text{NLO Sullivan et al.})$$

- ▶ Flagship measurement at Run II
- ▶ Dominant bkgds:  $Wjj$ ,  $tt$ , QCD
- ▶ Measure s- and t-channel cross sections separately
- ▶ First direct probe of  $|V_{tb}|$

**TeV:  $0.88 \pm 0.11 \text{ pb}$**

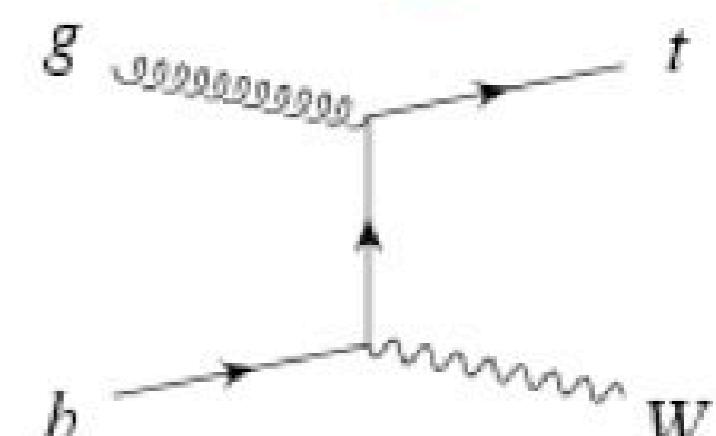
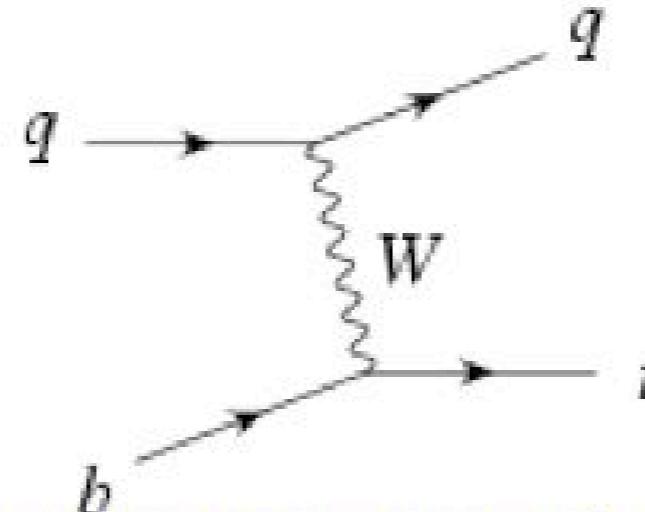
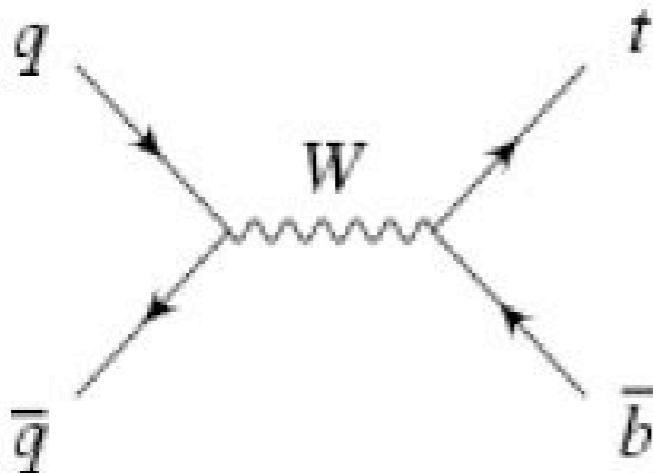
**$1.98 \pm 0.25 \text{ pb}$**

**$<0.1 \text{ pb}$**

**LHC:  $10.6 \pm 1.1 \text{ pb}$**

**$246.6 \pm 0.25 \text{ pb}$**

**$62.0^{+16.6}_{-3.6} \text{ pb}$**



Harris, Laenen, Phaf, Sullivan, Weinzierl, PRD 66 (02) 054024  
Sullivan hep-ph/0408049

Tait, PRD 61 (00) 034001  
Belyaev, Boos, PRD 63 (01) 034012

# Systematics

## Monte Carlo Systematic Uncertainties

### Components affecting normalization

$\sigma_{t\bar{t}}$ theory and mass	18 %
$\sigma_{s(t)}$ theory	15 %(16 %)
Jet Fragmentation	5 %
$e$ ( $\mu$ ) ID	4 %(5 %)

### Components affecting shape and normalization

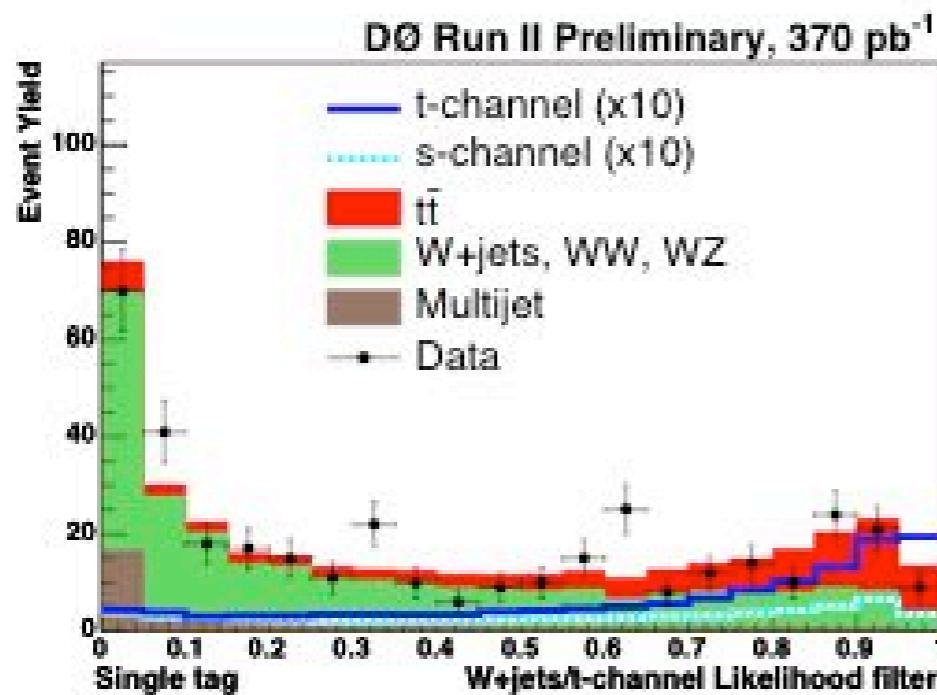
Single (double) $b$ -tagging modeling	6 %(17 %)
Jet Energy Scale	1-5 %
Trigger Modeling	2-7 %
Jet ID	1-4 %

# DØ Likelihood Analysis w/ $370 \text{ pb}^{-1}$

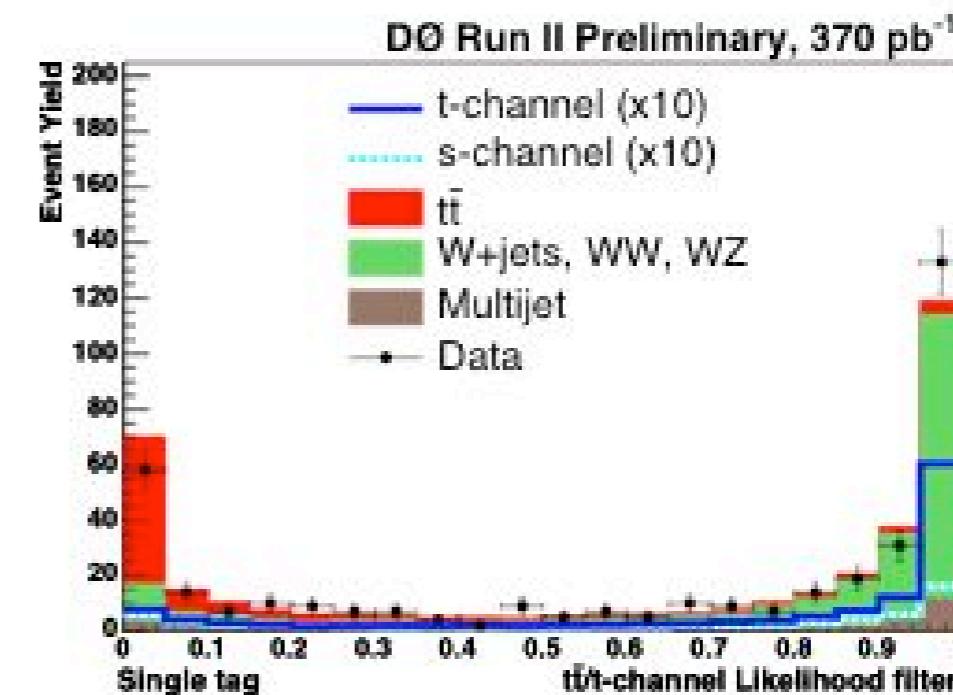
- We performed a likelihood analysis using variables that show discrimination between single top signal and background where the likelihood is defined as

$$\mathcal{L}(\vec{x}) = \frac{\mathcal{P}_{\text{Signal}}(\vec{x})}{\mathcal{P}_{\text{Signal}}(\vec{x}) + \mathcal{P}_{\text{Background}}(\vec{x})} \quad \mathcal{P}_{S|B} = \prod_{\text{Vars}} \mathcal{P}_i$$

- We create two likelihoods for each signal: One using Wbb as background and the other using ttbar as background.
- Below is the output when the trained likelihood is applied to background, signal, and data events



Wbb background

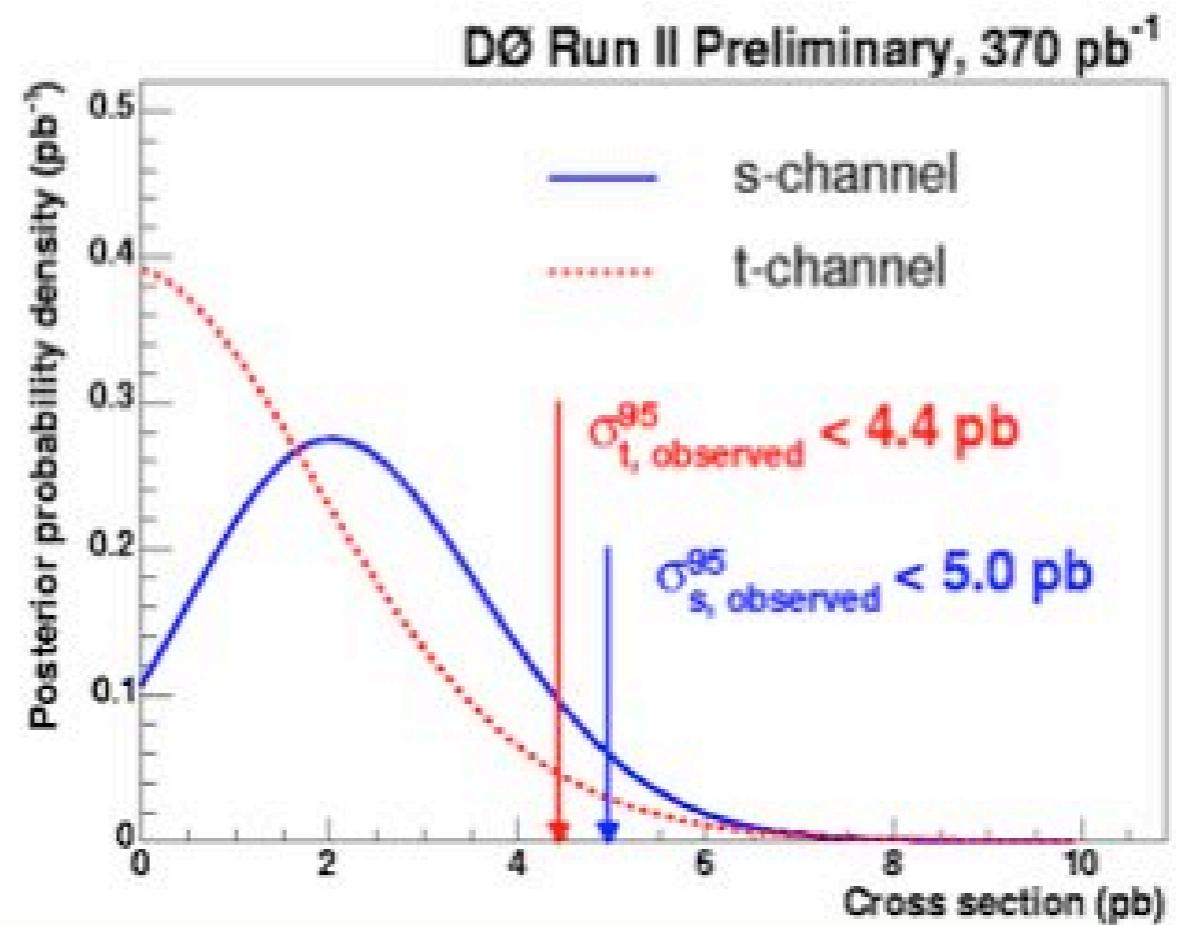


ttbar background

# 95% CL Limits Using $370 \text{ pb}^{-1}$

- ◆ We see no excess of signal events above the estimated background so we can set 95% CL limits on each channel's production cross section
- ◆ We use a 2D histogram of the s-channel vs t-channel likelihood output as input to a binned likelihood to estimate the cross section limits
  - ❖  $\sigma_{t\text{-channel}} < 4.4 \text{ pb}$
  - ❖  $\sigma_{s\text{-channel}} < 5.0 \text{ pb}$
- ◆ Leading systematic errors:
  - ❖ b-tagging efficiency (6-17%)
  - ❖ Jet Energy Scale (5%)
  - ❖ Trigger modeling (5%)
  - ❖ Object ID (5%)
  - ❖ Theory cross section (18%)

Posterior Density Function

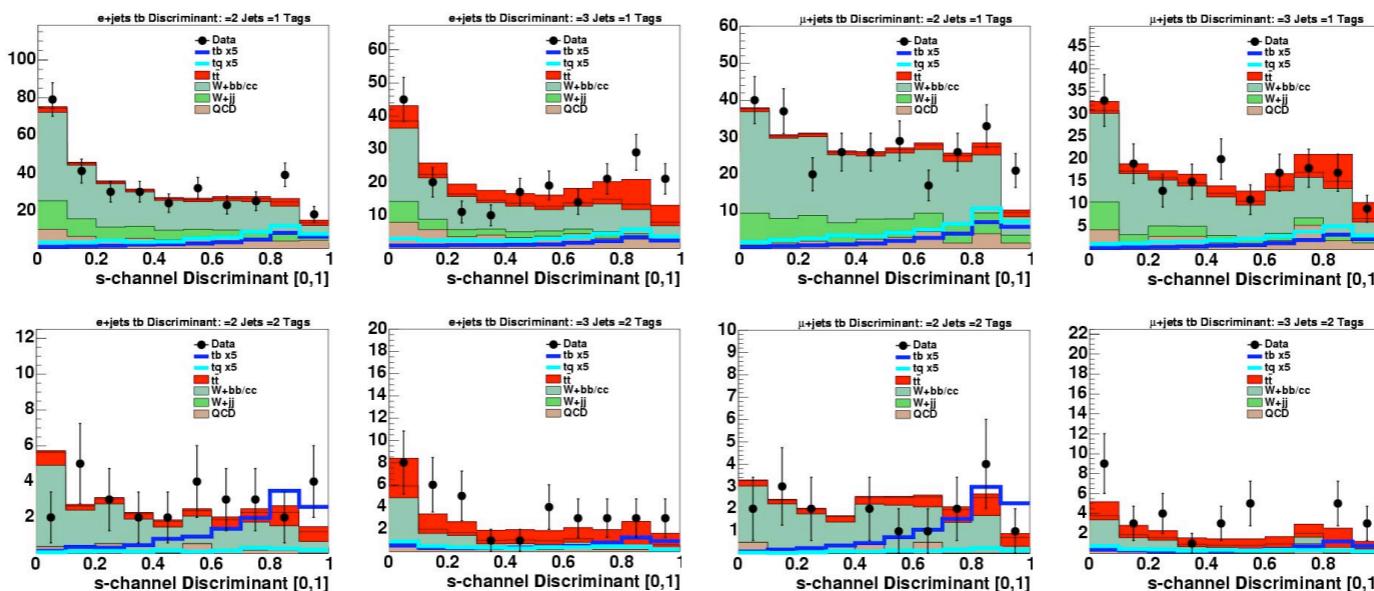


# Observed Limits

95 % CL Expected/Observed Upper Limits in pb	<i>s</i> -channel, $tb$	<i>t</i> -channel, $tqb$
CDF Run II, $162 \text{ pb}^{-1}$	12.1/13.6	11.2/10.1
DØ Run II, $230 \text{ pb}^{-1}$		
Cuts	9.8/10.6	12.4/11.3
DTs & binned likelihood	4.5/8.3	6.4/8.1
NNs & binned likelihood	4.5/6.4	5.8/5.0
DØ Run II, $370 \text{ pb}^{-1}$		
LHs & binned likelihood	<b>3.3/5.0</b>	<b>4.3/4.4</b>
NLO theory	= 0.88	= 1.98

# Limit Setting Strategy

- ◆ Instead of cutting on discriminant value, we use it to set limits using a binned likelihood method
- ◆ This takes advantage of the full shape information for the discriminant.



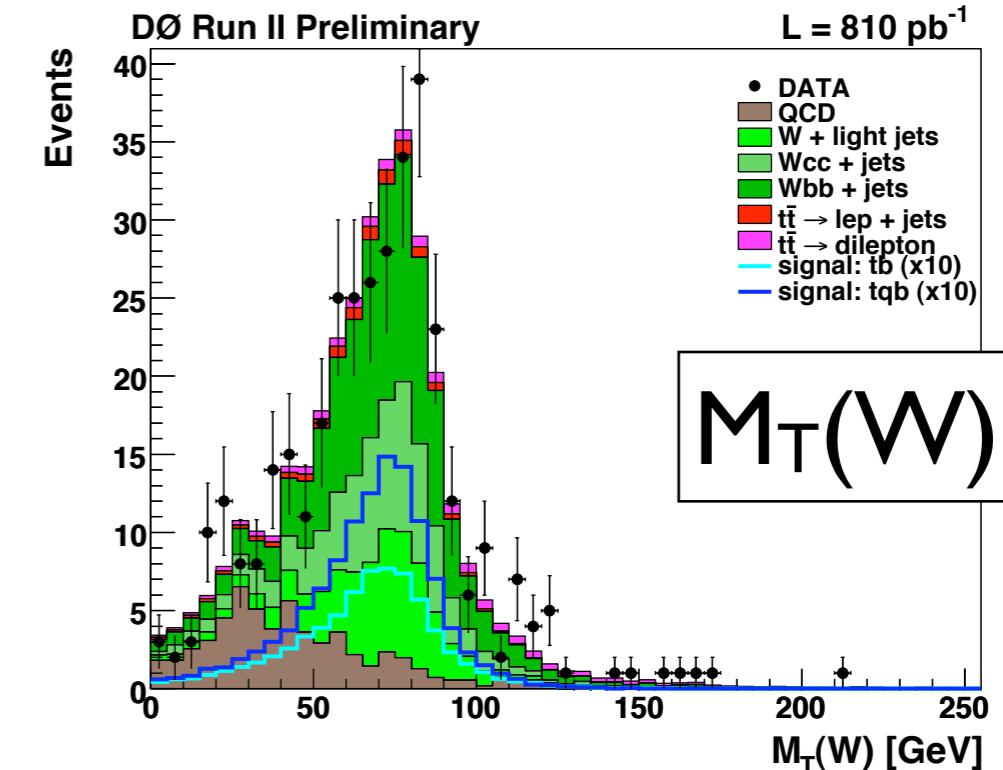
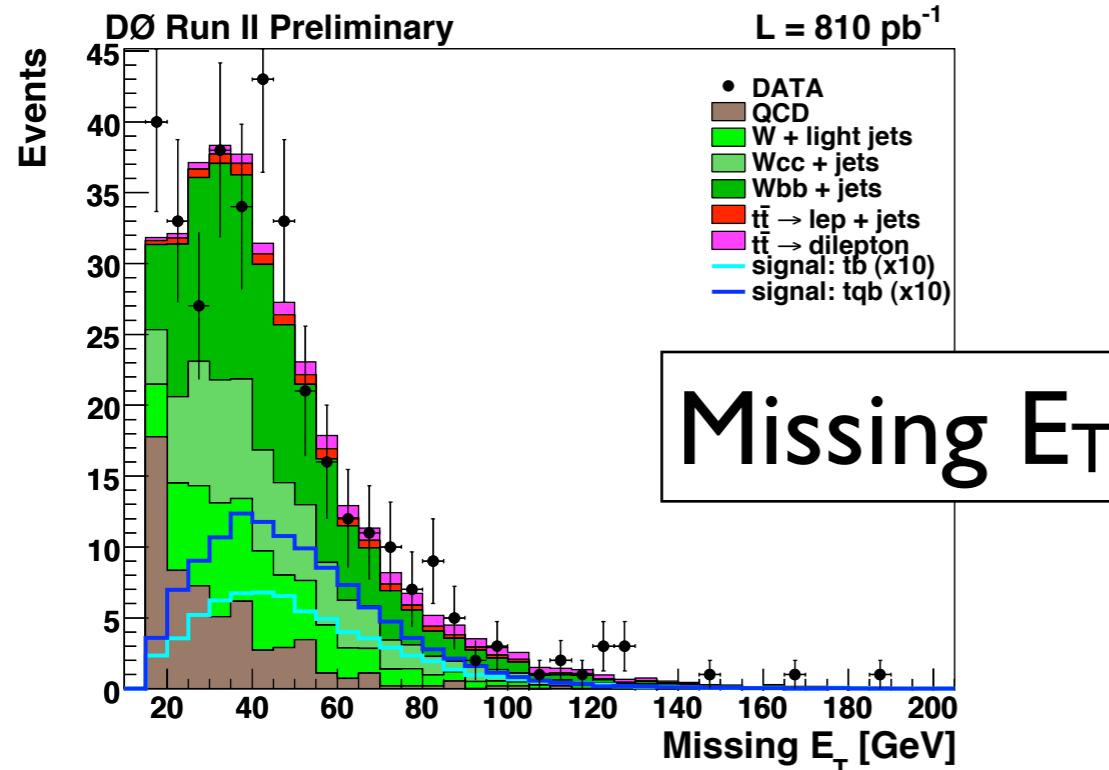
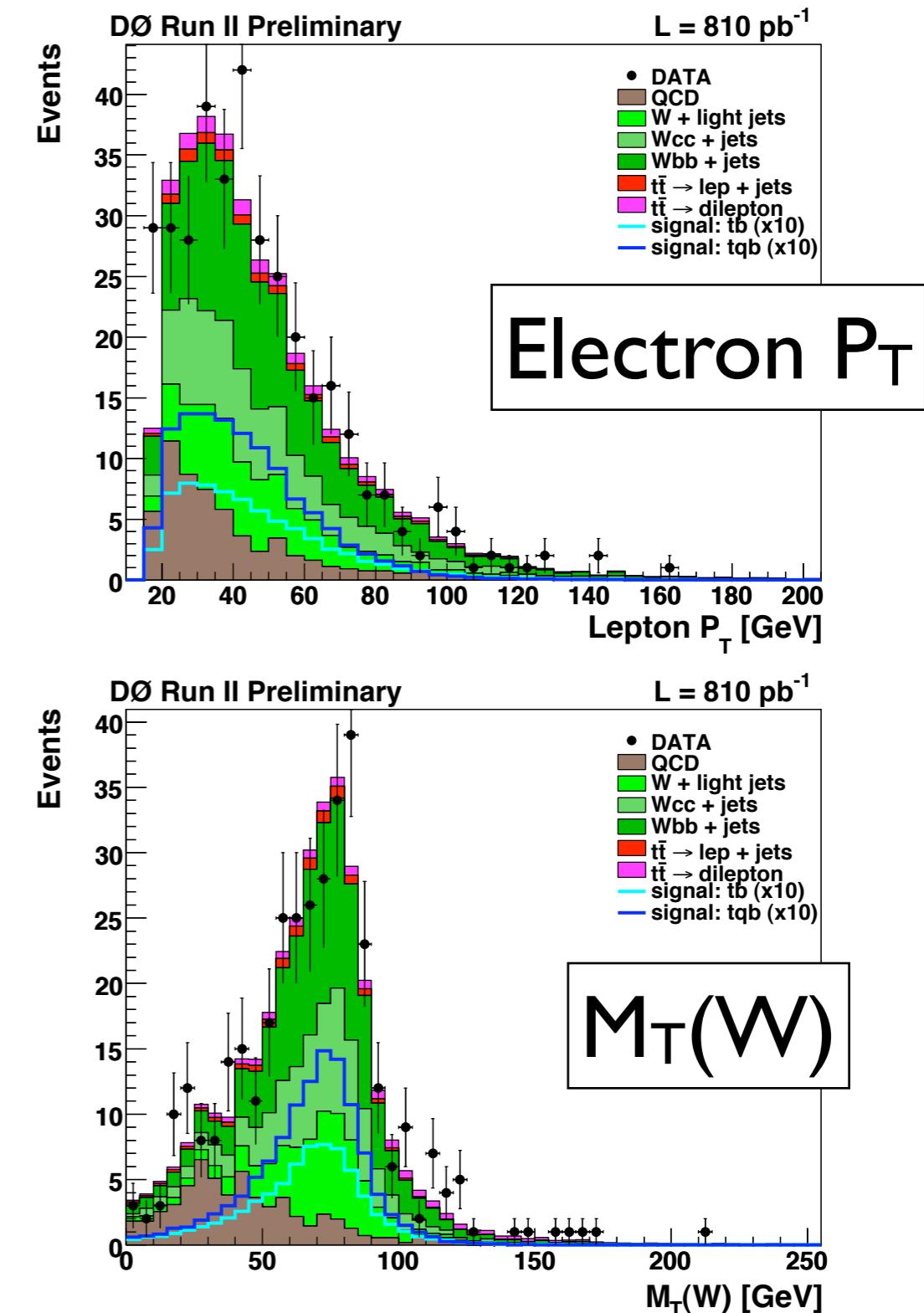
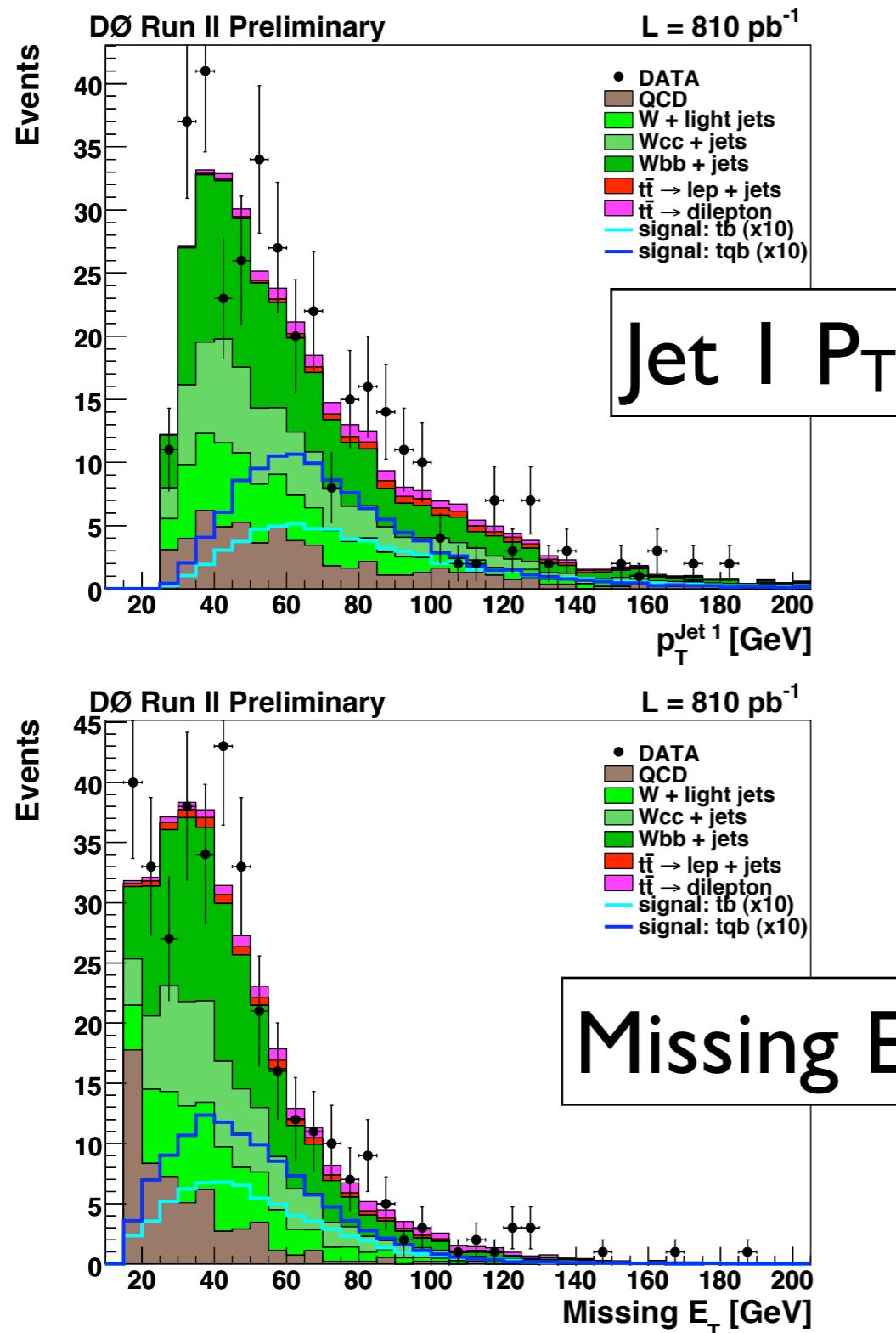
$$P(s|n) = \frac{P(n|s)\pi(s)}{\pi(n)}$$

$$P(n|s) = \prod_i \mathcal{L}_i = \prod_i \frac{(s_i + b_i)^{n_i}}{n_i!} e^{-(s_i + b_i)}$$

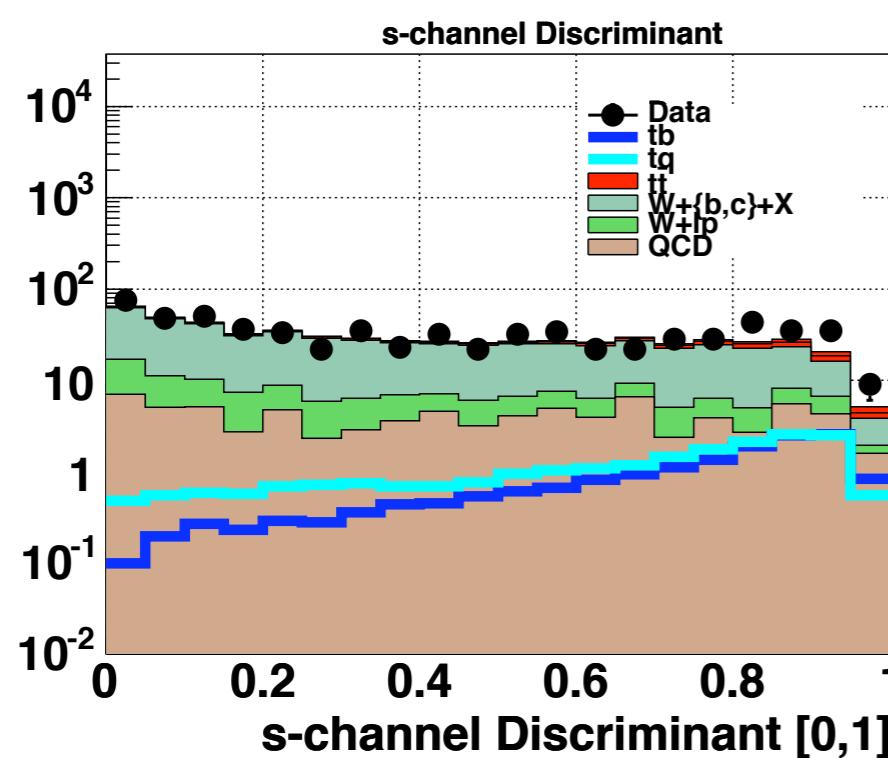
$$\pi(n) = \int \prod_i \mathcal{L}_i$$

- ◆ CL defined by integral of  $P(s|n)$

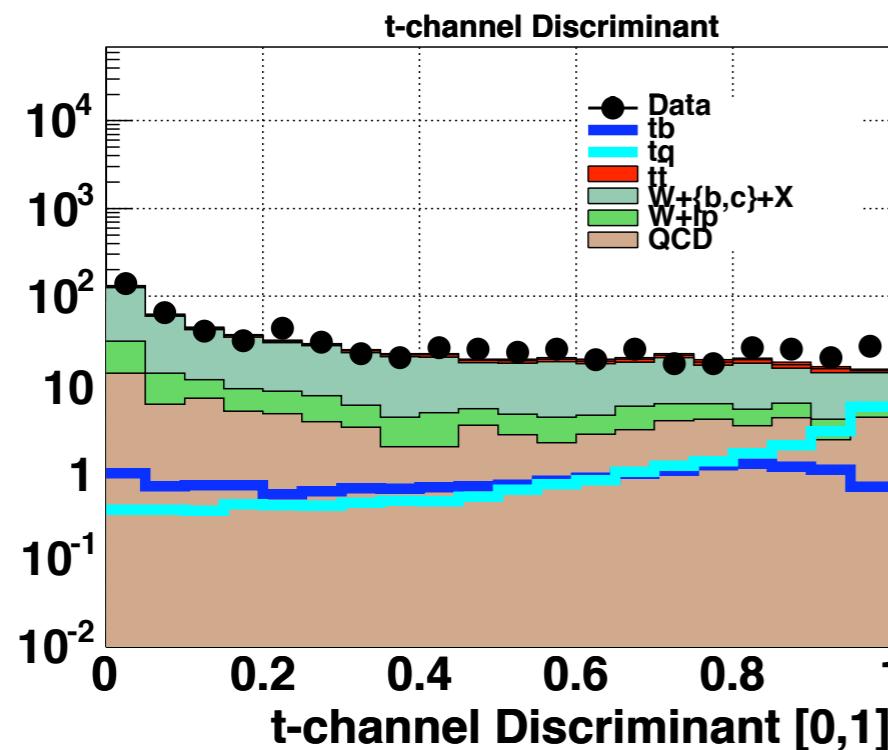
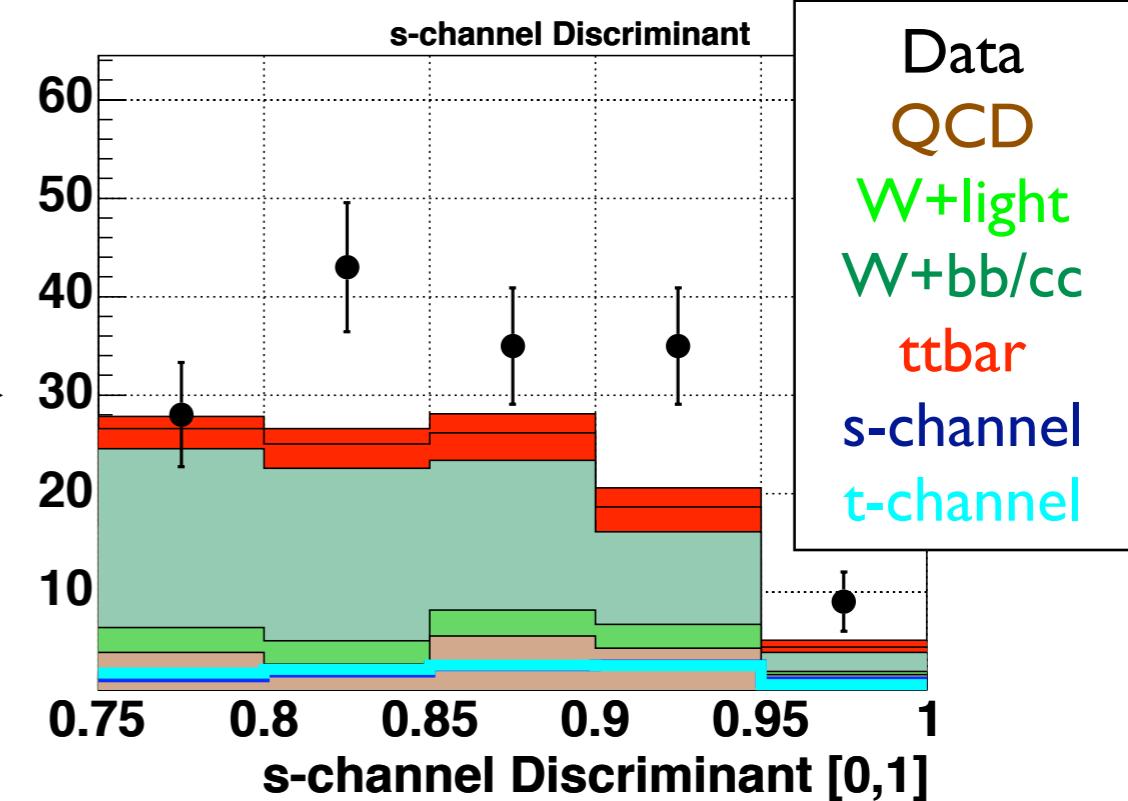
# Data / Background Comparison (Electron Channel)



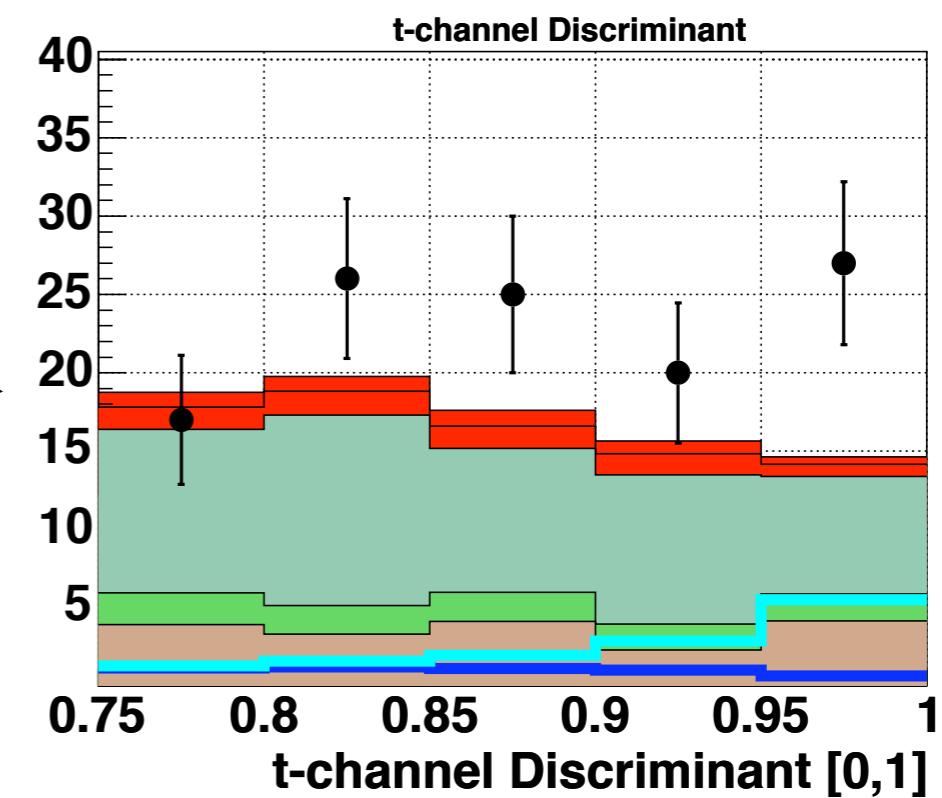
# Discriminants with $\sim 800 \text{ pb}^{-1}$ Dataset



Zoom →

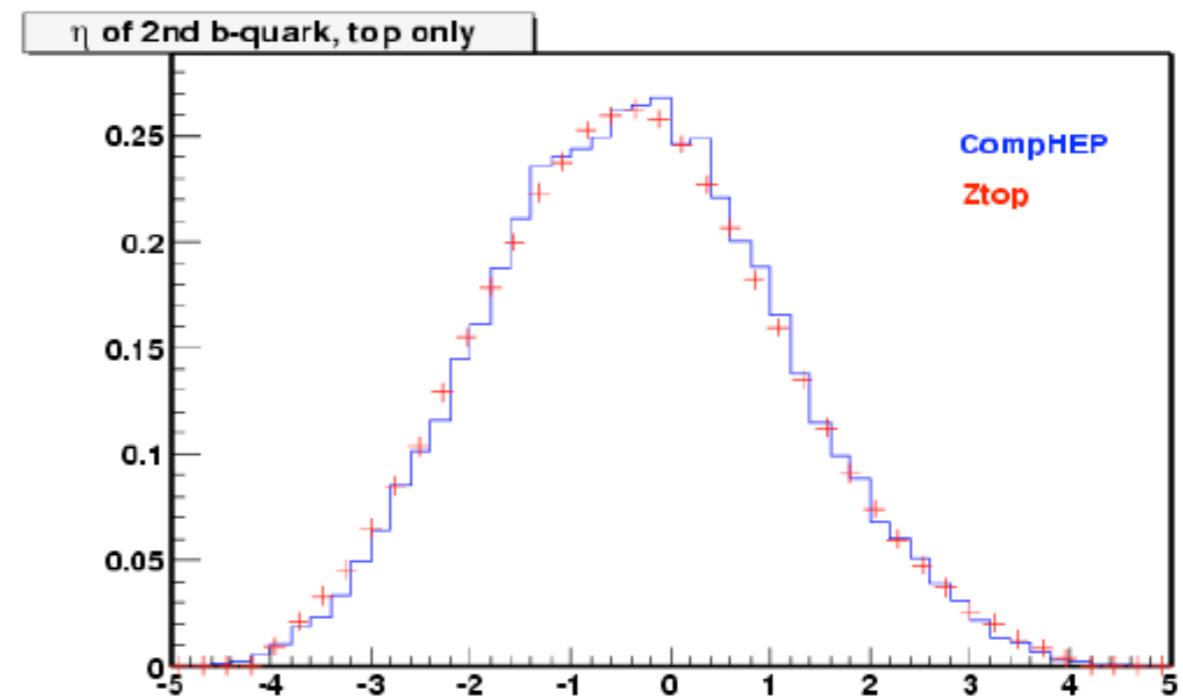
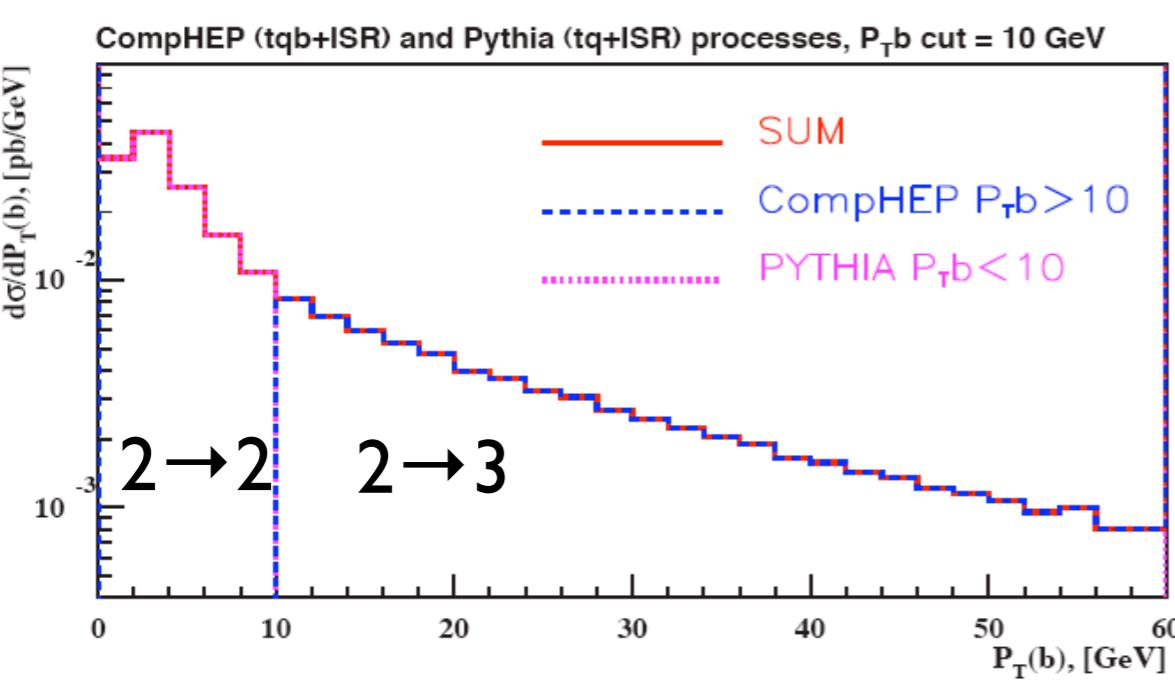
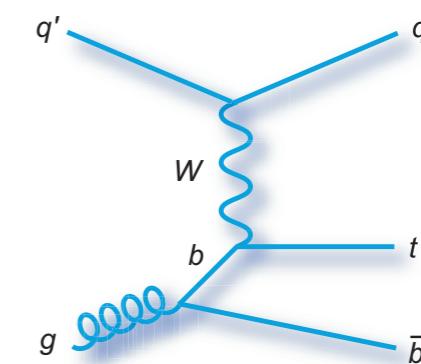


Zoom →



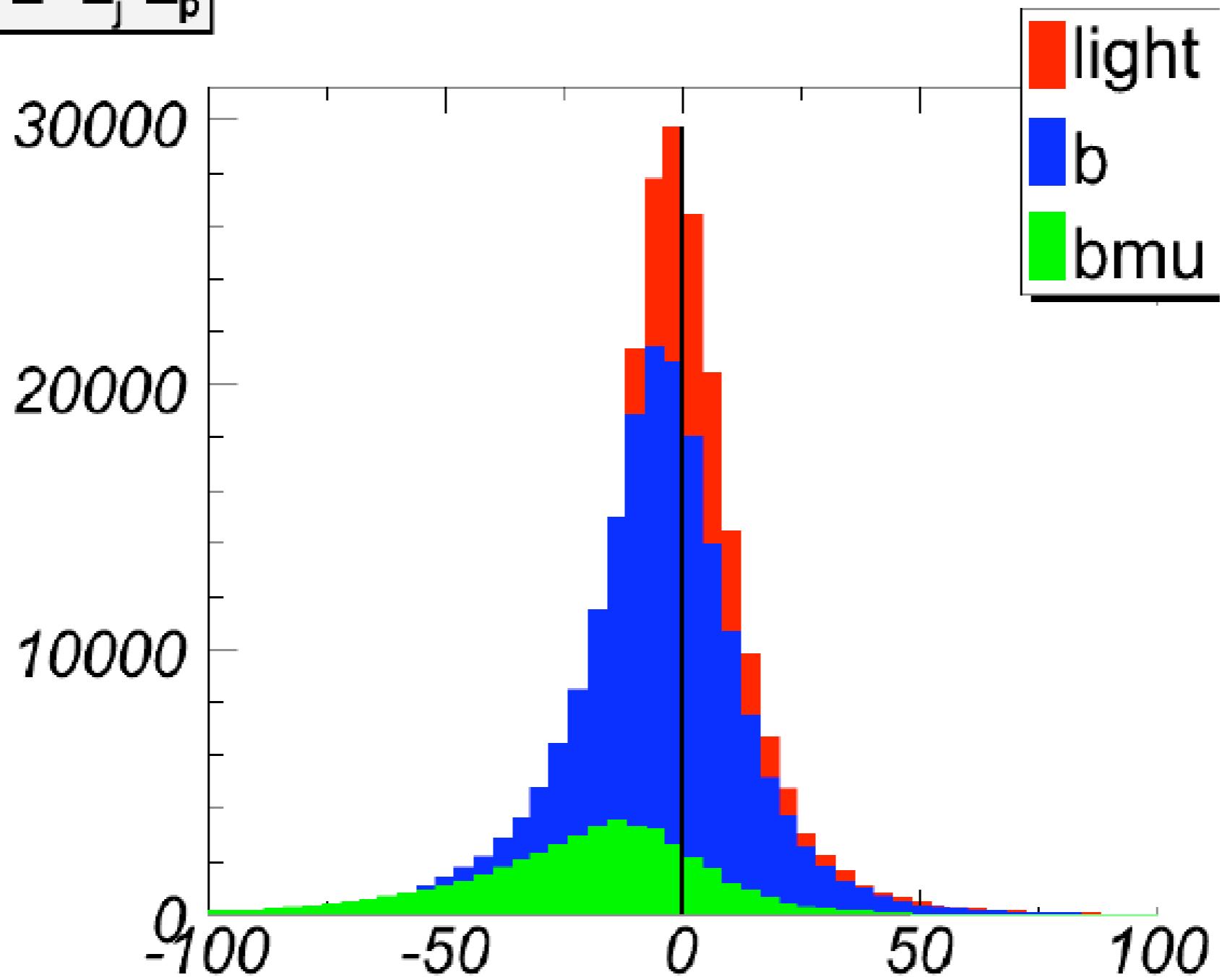
# Single Top Signal Modeling

- ◆ We use COMPHEP to model our signal using a 2->2 and 2->3 matching procedure using the b quark Pt dependence
  - ❖ Below b Pt of 10 GeV use Pythia 2->2 diagrams
  - ❖ After 10 GeV use CompHEP 2->3 diagrams.
- ◆ Agreement is great with NLO distributions from Ztop & MCFM
  - ❖ CompHEP is effective single top NLO generator



# Transfer Functions

$$\Delta E = E_j - E_p$$

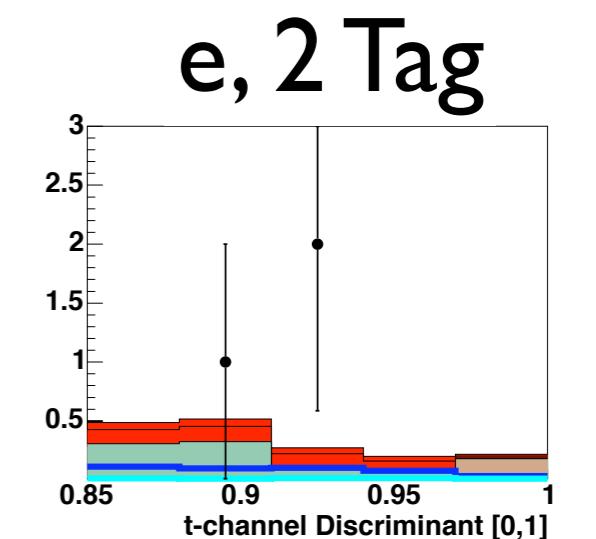
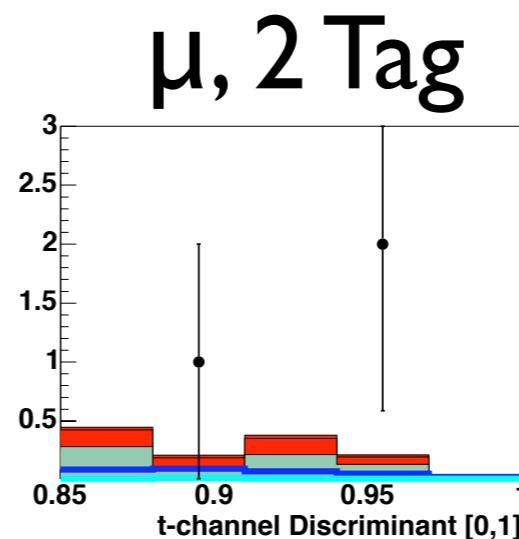
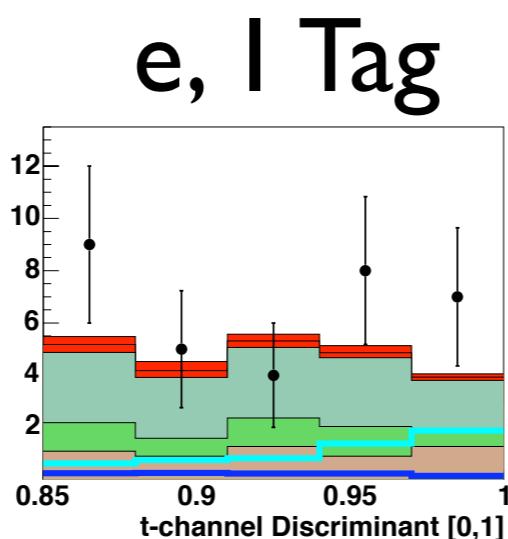
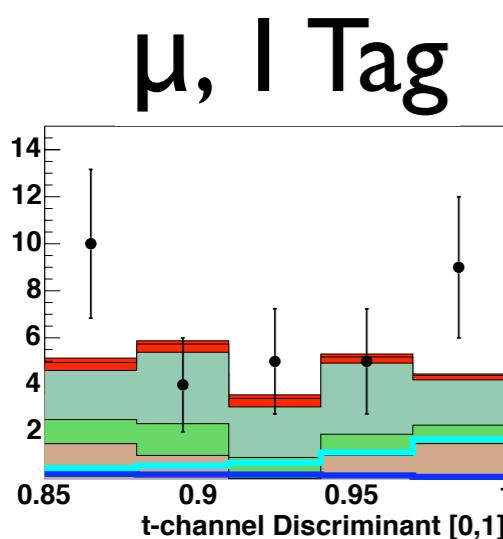


# $|V_{tb}|$

- ◆ Most measurements assume unitarity
- ◆ Assume:  $(|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1)$ , then  $V_{tb}$  is highly constrained
- ◆  $0.9990 < |V_{tb}| < 0.9993$  @ 90% CL
- ◆ If you remove the unitarity constraint, then  $V_{tb}$  can be virtually anything
- ◆  $0.08 < |V_{tb}| < 0.9993$  @ 90% CL
- ◆ If you assume unitarity, you can measure  $V_{tb}$  by measuring the top decay into b quarks vs. all quarks

# Limit Setting Strategy

- ◆ Optimize each channel separately and combine when setting limits
  - ❖ 4 orthogonal channels: {electrons, muons} x {single and double tags}
- ◆ Use full shape information by using a binned likelihood

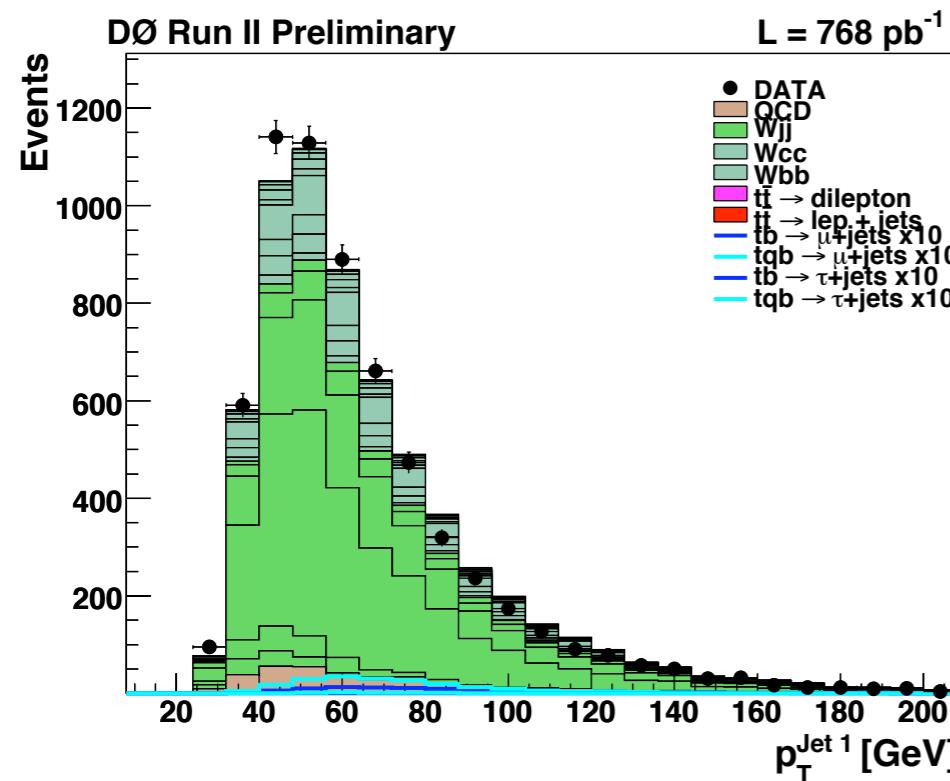


Combined Expected Limits

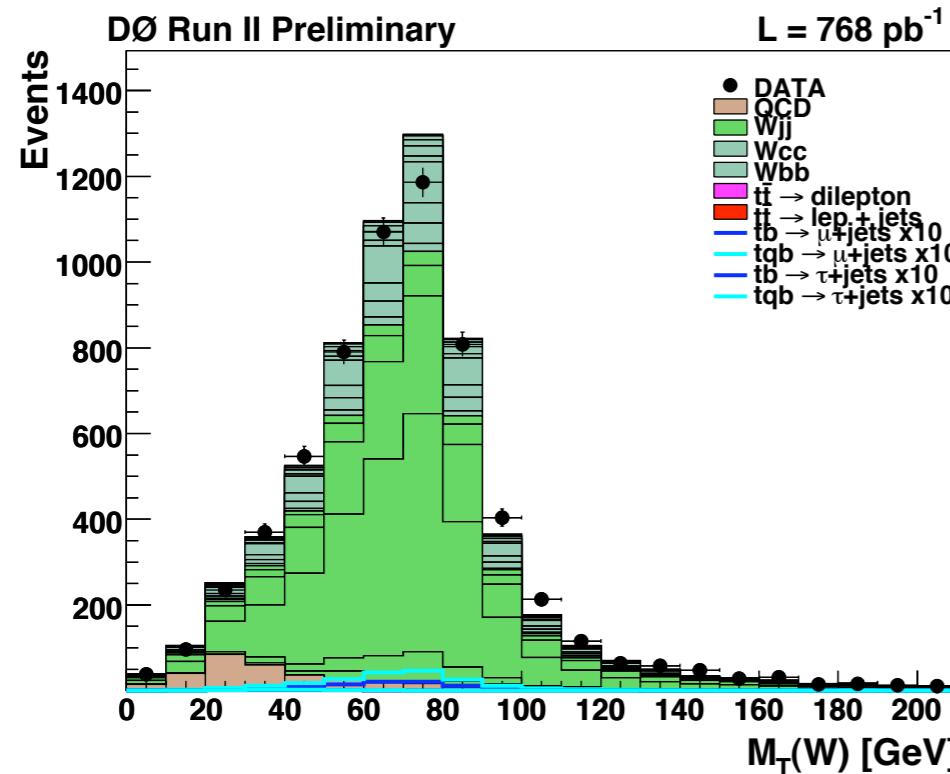
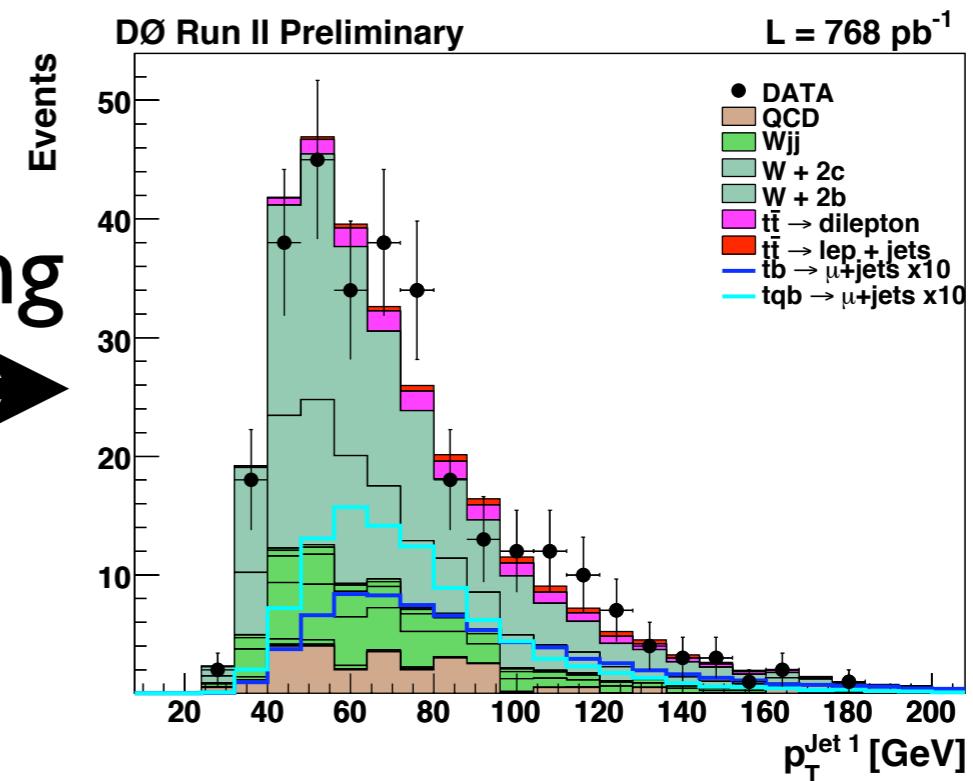
$$\sigma_s^{95} < 1.6 \text{ pb}$$

$$\sigma_t^{95} < 2.5 \text{ pb}$$

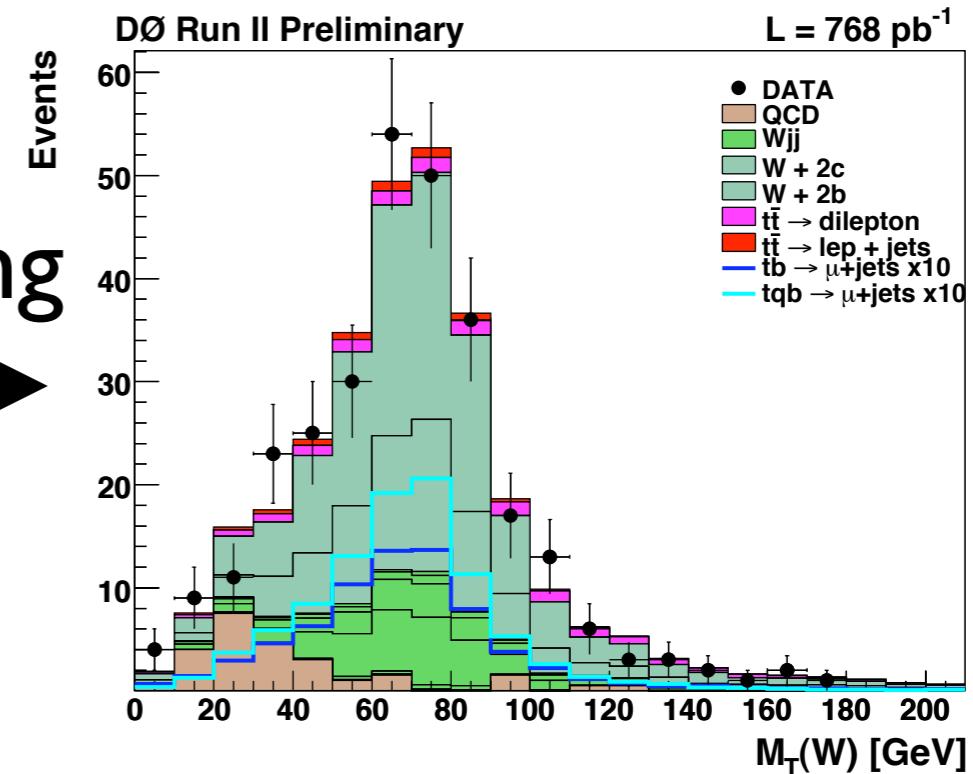
# Background Estimation Before/After Tagging



Tagging  
→



Tagging  
→

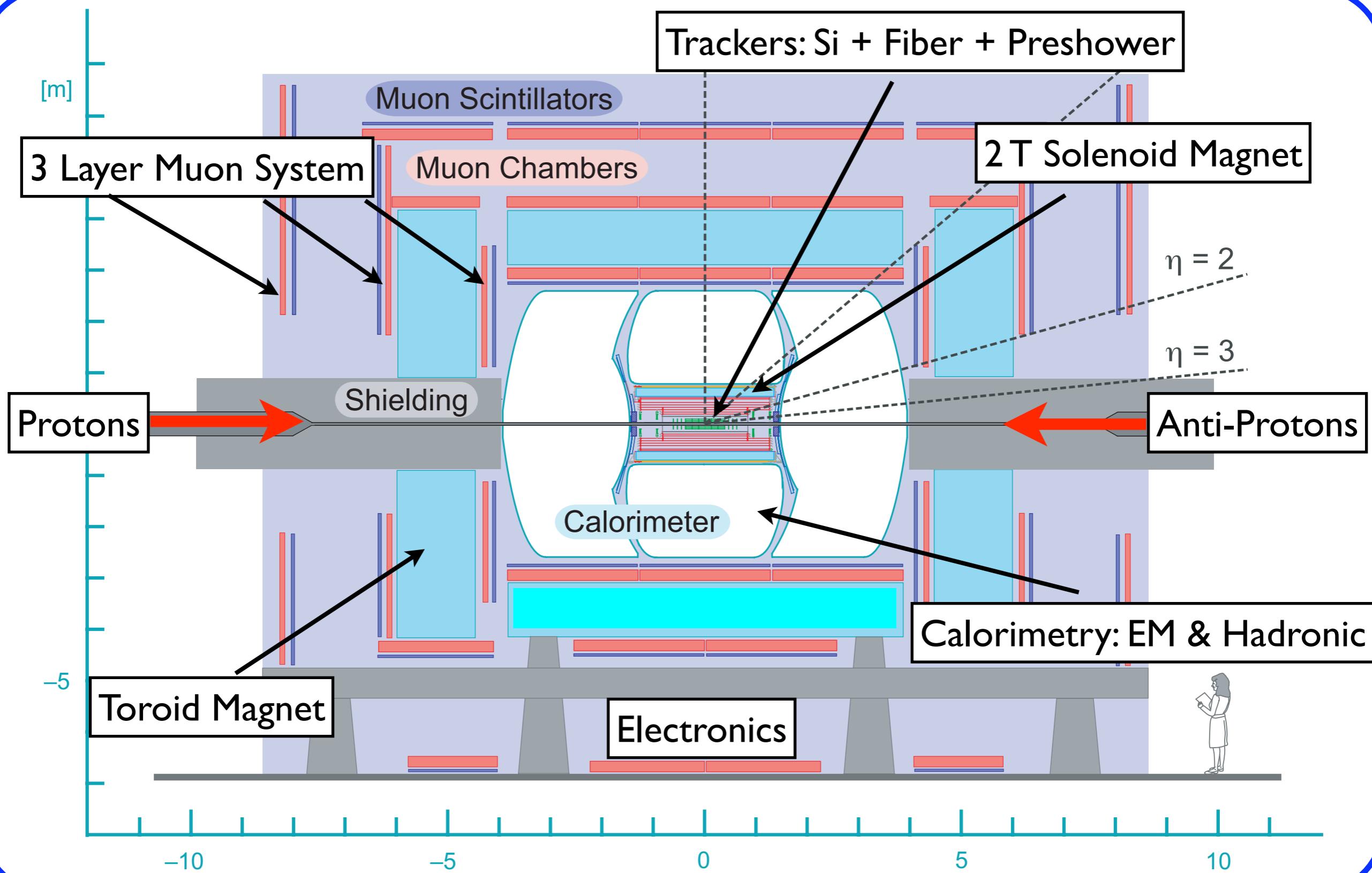


# Yields After Tagging

	Yields
Data Events	665
s-channel (tb)	16.4
t-channel (tqb)	21.9
W+jets	481
ttbar	45.9
QCD Heavy flavor	81.7

Observed	665
Signal	38.2
Background	609

# Run II DØ Detector



# Background Normalization

- ◆ Our signal and ttbar background is normalized to the NLLO cross section times the integrated luminosity.
- ◆ W+jets and QCD are normalized to the data by the "Matrix Method".
- ◆ We do this by writing two equations involving the number of W+jets and QCD events
  - $N_{\text{Loose}} = N_{\text{QCD}} + N_{\text{W+jets}}$
  - $N_{\text{Tight}} = \epsilon_{\text{QCD}} N_{\text{QCD}} + \epsilon_{\text{W+jets}} N_{\text{W+jets}}$
  - ❖ where the Loose and Tight samples are defined such that one has a mix of QCD and W+jets while the other has mostly W+jets.
  - ❖  $\epsilon_{\text{QCD}}$  is the efficiency for muons from QCD events to pass the "tight" cut and  $\epsilon_{\text{W+jets}}$  is the efficiency for muons from W decays to pass the cut.
- ◆ Knowing the two efficiencies and the loose and tight sample size in data, you can solve for the expected number of QCD and W+jets events.

# B-tagging Improvement

